

Electroweak Precision Physics from Low to High Energies

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thanks go to:

A. Ritz, D. Stöckinger and G. Weiglein

1. Introduction and motivation
2. The anomalous magnetic moment of the muon
3. Electric dipole moments
4. Electroweak Precision Observables in the SM
5. Electroweak Precision Observables in the MSSM
6. Conclusions

1. Introduction and motivation

Q: Which Lagrangian describes the world?

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A: Ummm . . . Let's start differently!

1. Introduction and motivation

Interesting (new) physics models :

- SM:
 - tested far beyond expectations
- 2HDM:
 - two Higgs doublets more natural than one
- MSSM:
 - solves hierarchy problem
 - automatic electroweak symmetry breaking
 - gauge coupling unification
 - cold dark matter candidate
- Little Higgs:
 - (partially) solves the hierarchy problem
 - cold dark matter candidate
- Extra dimensions:
 - solves the hierarchy problem
 - cold dark matter candidate
- ...

⇒ pick your favorite model now (I pick the MSSM)

Q: Which Lagrangian describes the world?

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A: Let's try again . . .

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Q': What describes the world better: SM or your NPM (new physics model) ?

A: Two possible ways:

- Search for new NPM particles

new NPM particles found
↔
SM ruled out

Problem:

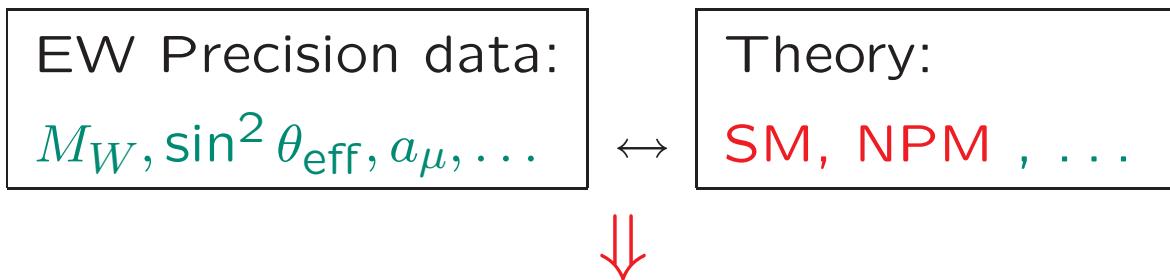
NPM particles are too heavy for todays
colliders, only lower limits of $\sim \mathcal{O}(100 \text{ GeV})$.

- waiting for Tevatron (2008/09 . . . ?)
- waiting for LHC (2009/10 . . . ? cooling problems . . .)

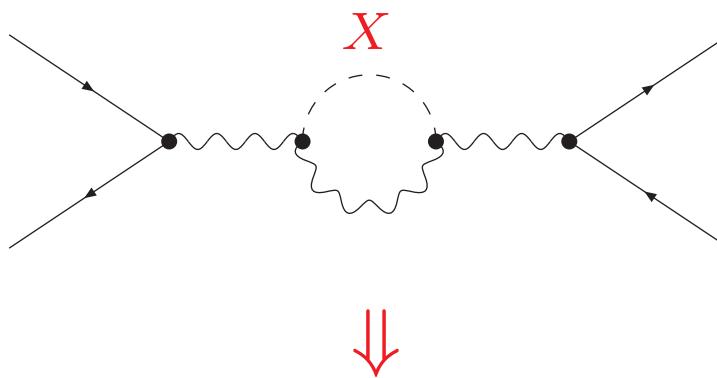
- Search for indirect effects of NPM
via Precision Observables

Precision Observables (POs):

Comparison of electro-weak precision observables with theory:



Test of theory at quantum level: Sensitivity to loop corrections



Very high accuracy of measurements and theoretical predictions needed

- Which model fits better?
- Does the prediction of a model contradict the experimental data?

I pick the MSSM:

Supersymmetry (SUSY) : Symmetry between

Bosons \leftrightarrow Fermions

$$Q \text{ |Fermion} \rangle \rightarrow \text{|Boson} \rangle$$

$$Q \text{ |Boson} \rangle \rightarrow \text{|Fermion} \rangle$$

Simplified examples:

$$Q \text{ |top, } t \rangle \rightarrow \text{|scalar top, } \tilde{t} \rangle$$

$$Q \text{ |gluon, } g \rangle \rightarrow \text{|gluino, } \tilde{g} \rangle$$

\Rightarrow each SM multiplet is enlarged to its double size

Unbroken SUSY: All particles in a multiplet have the same mass

Reality: $m_e \neq m_{\tilde{e}}$ \Rightarrow SUSY is broken . . .

. . . via soft SUSY-breaking terms in the Lagrangian (added by hand)

SUSY particles are made heavy: $M_{\text{SUSY}} = \mathcal{O}(1 \text{ TeV})$

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$[u, d, c, s, t, b]_{L,R}$	$[e, \mu, \tau]_{L,R}$	$[\nu_{e,\mu,\tau}]_L$	Spin $\frac{1}{2}$
$[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}]_{L,R}$	$[\tilde{e}, \tilde{\mu}, \tilde{\tau}]_{L,R}$	$[\tilde{\nu}_{e,\mu,\tau}]_L$	Spin 0
g	$\underbrace{W^\pm, H^\pm}_{\text{}}$	$\underbrace{\gamma, Z, H_1^0, H_2^0}_{\text{}}$	Spin 1 / Spin 0
\tilde{g}	$\tilde{\chi}_{1,2}^\pm$	$\tilde{\chi}_{1,2,3,4}^0$	Spin $\frac{1}{2}$

Enlarged Higgs sector: Two Higgs doublets

Problem in the MSSM: many scales

\tilde{t}/\tilde{b} sector of the MSSM: (scalar partner of the top/bottom quark)

Stop, sbottom mass matrices ($X_t = A_t - \mu^*/\tan\beta$, $X_b = A_b - \mu^*\tan\beta$):

$$\mathcal{M}_{\tilde{t}}^2 = \begin{pmatrix} M_{\tilde{t}_L}^2 + m_t^2 + DT_{t_1} & m_t X_t^* \\ m_t X_t & M_{\tilde{t}_R}^2 + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m_{\tilde{t}_1}^2 & 0 \\ 0 & m_{\tilde{t}_2}^2 \end{pmatrix}$$

$$\mathcal{M}_{\tilde{b}}^2 = \begin{pmatrix} M_{\tilde{b}_L}^2 + m_b^2 + DT_{b_1} & m_b X_b^* \\ m_b X_b & M_{\tilde{b}_R}^2 + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m_{\tilde{b}_1}^2 & 0 \\ 0 & m_{\tilde{b}_2}^2 \end{pmatrix}$$

mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

soft SUSY-breaking parameters A_t, A_b also appear in ϕ - \tilde{t}/\tilde{b} couplings

$$SU(2) \text{ relation} \Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$$

\Rightarrow relation between $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$\begin{aligned} V = & m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.}) \\ & + \underbrace{\frac{g'^2 + g^2}{8}}_{\text{gauge couplings, in contrast to SM}} (H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}}_{\text{gauge couplings, in contrast to SM}} |H_1 \bar{H}_2|^2 \end{aligned}$$

physical states: h^0, H^0, A^0, H^\pm

Goldstone bosons: G^0, G^\pm

Input parameters: (to be determined experimentally)

$$\tan \beta = \frac{v_2}{v_1}, \quad M_A^2 = -m_{12}^2(\tan \beta + \cot \beta)$$

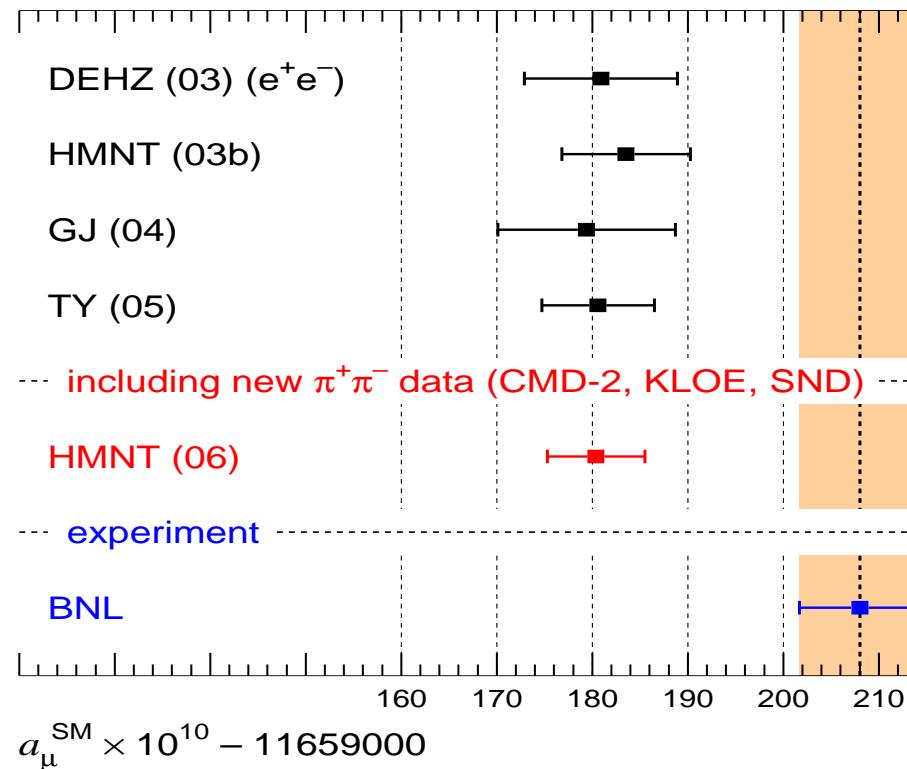
2. The anomalous magnetic moment of the muon

$$a_\mu \equiv (g - 2)_\mu / 2$$

Overview about the current experimental and SM (theory) result:

[*g-2 Collaboration, hep-ex/0602035*]

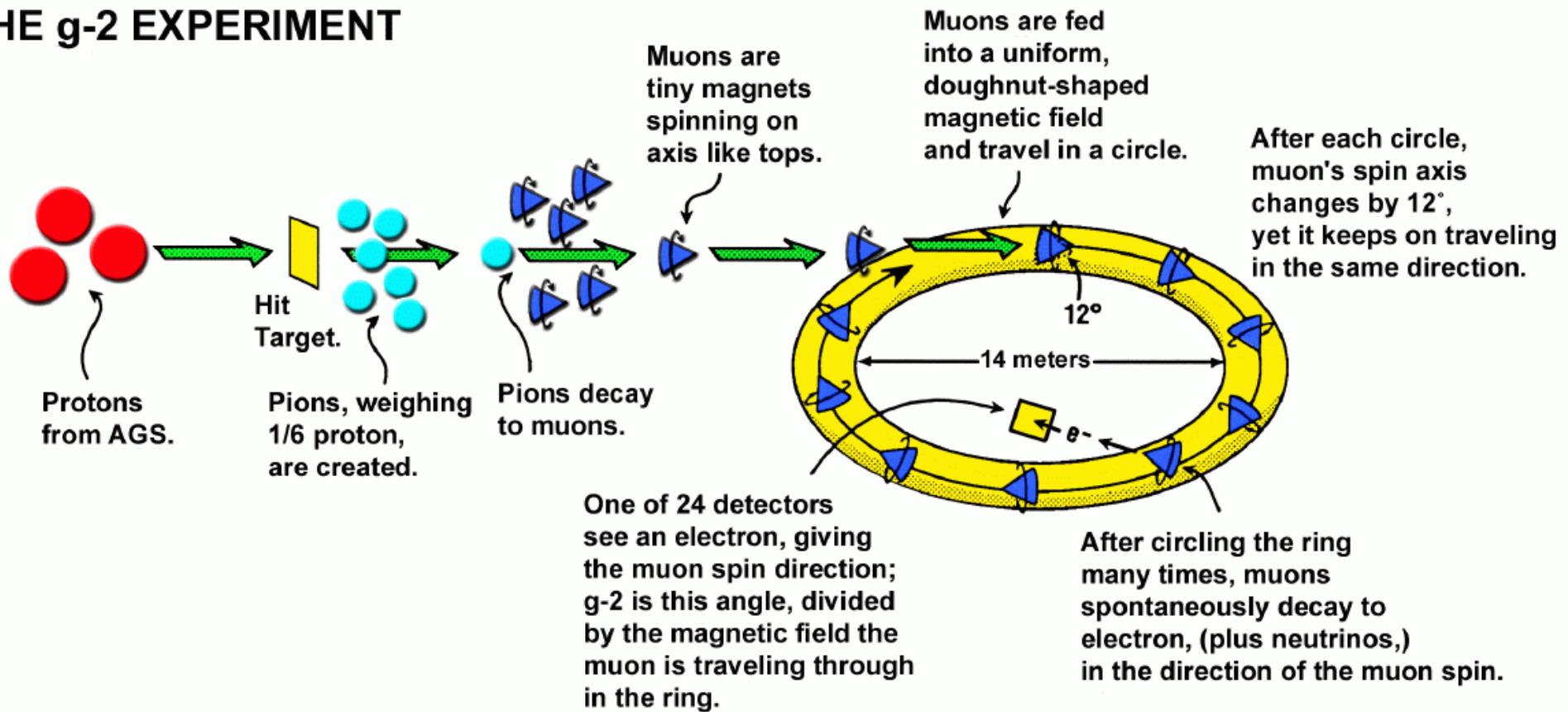
$\rightarrow T$



$$a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} \approx (28 \pm 8) \times 10^{-10} : 3.4 \sigma$$

The $(g - 2)_\mu$ experiment:

LIFE OF A MUON: THE g-2 EXPERIMENT



Coupling of muon to magnetic field : $\mu - \mu - \gamma$ coupling

$$\bar{u}(p') \left[\gamma^\mu F_1(q^2) + \frac{i}{2m_\mu} \sigma^{\mu\nu} q_\nu F_2(q^2) \right] u(p) A_\mu \quad F_2(0) = a_\mu$$

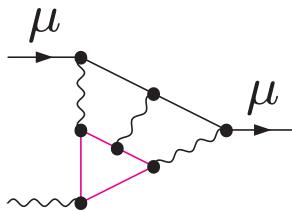
Current status of $(g - 2)_\mu$:

Experiment:

- 2001 - 2006: very stable development
- final error: 6×10^{-10} , still statistically dominated

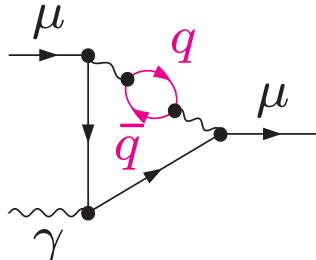
Theory:

- the light-by-light contribution:



2002: sign error discovered; since then stabilized

- the hadronic vacuum contribution:



problems with the τ data \Rightarrow hardly used anymore

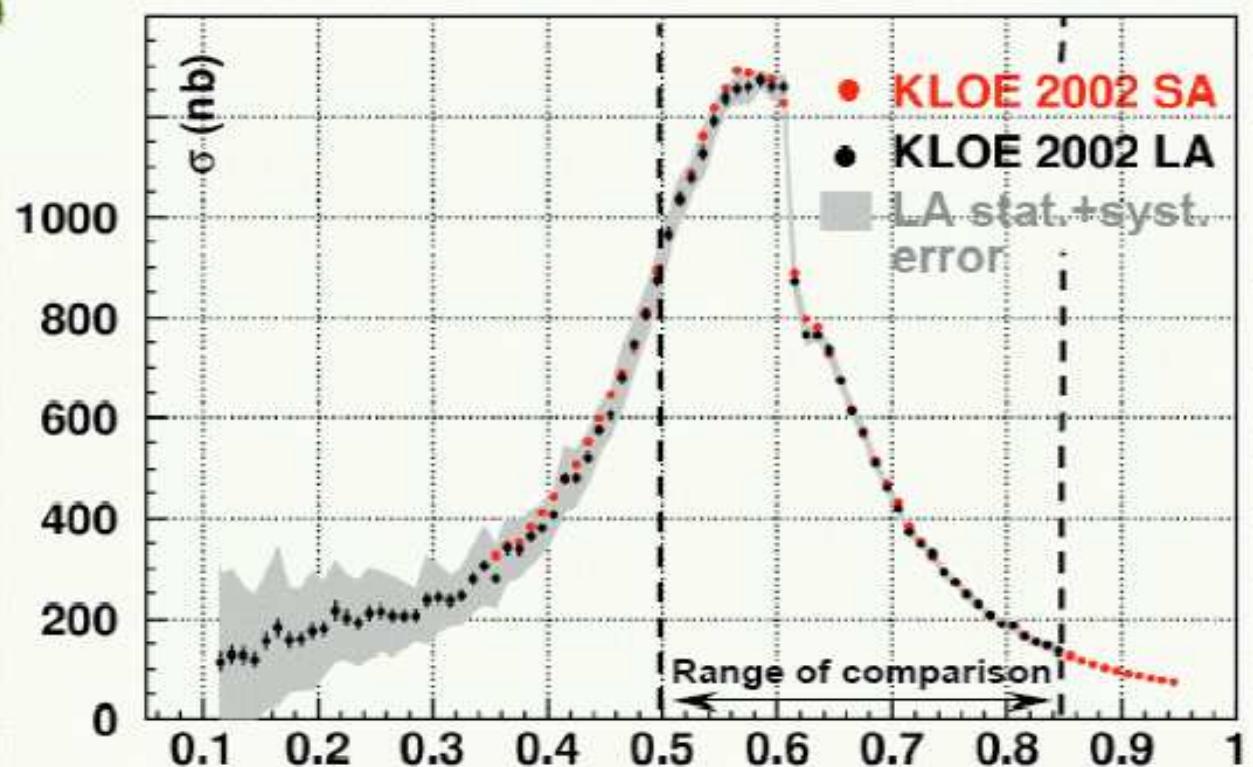
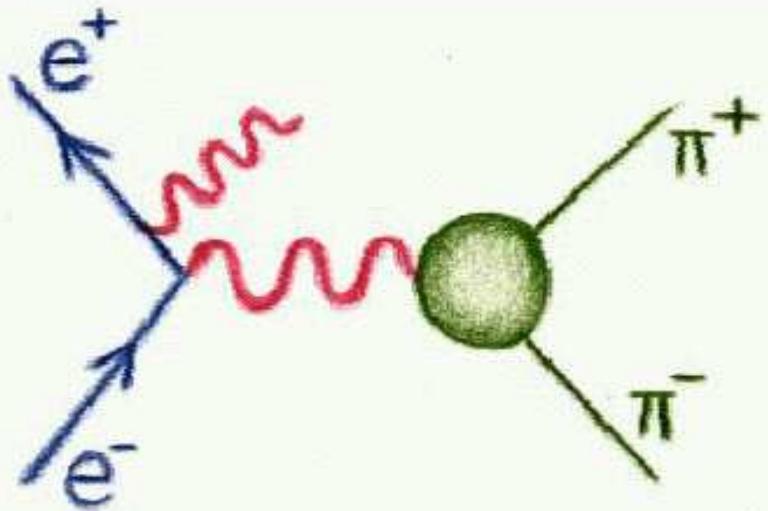
new 'direct' e^+e^- data from **CMD-II** and **SND**

\Rightarrow agrees well (also with old e^+e^- data)

new radiative return data from **KLOE** and B-factories

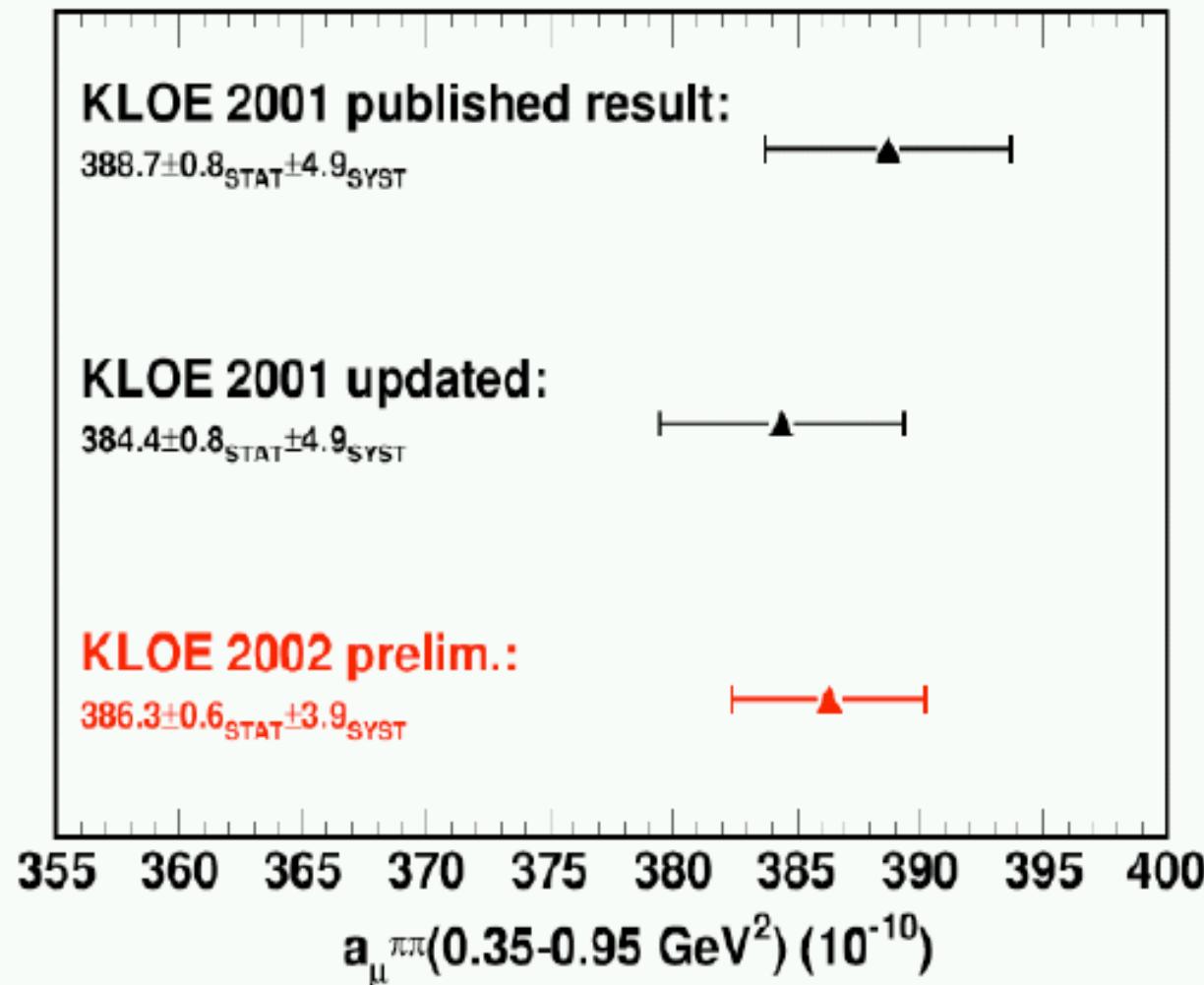
\Rightarrow agrees well with e^+e^- data

Stefan E. Müller



Summary of the small angle results:

Preliminary!!



new SM evaluations, based on new exp data for a_μ^{had} :

$$a_\mu(\text{Exp-SM}) = \left\{ \begin{array}{ll} [\text{HMNT '06}] & 28(8) \\ [\text{DEHZ '06}] & 28(8) \\ [\text{FJ '07}] & 29(9) \\ [\text{MRR '07}] & 29(9) \end{array} \right\} \times 10^{-10}$$

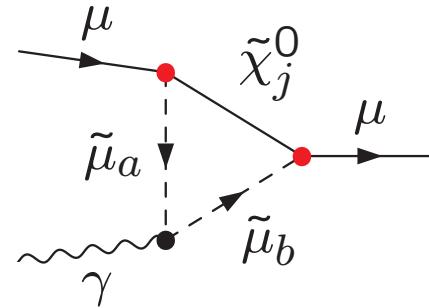
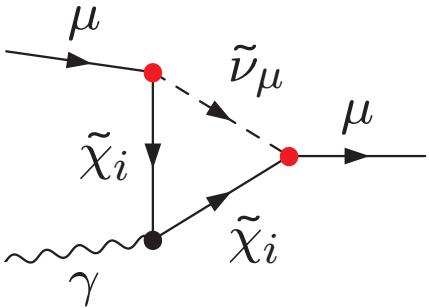
better agreement between evaluations, more precise,
larger deviation from exp than ever before



3σ deviation has now been definitely established

SUSY can easily explain the deviation:

Feynman diagrams for MSSM 1L corrections:



- Diagrams with chargino/sneutrino exchange
- Diagrams with neutralino/smuon exchange

Enhancement factor as compared to SM:

$$\mu - \tilde{\chi}_i^\pm - \tilde{\nu}_\mu : \sim m_\mu \tan \beta$$

$$\mu - \tilde{\chi}_j^0 - \tilde{\mu}_a : \sim m_\mu \tan \beta$$

$$\text{SM, EW 1L: } \frac{\alpha}{\pi} \frac{m_\mu^2}{M_W^2}$$

$$\text{MSSM, 1L: } \frac{\alpha}{\pi} \frac{m_\mu^2}{M_{\text{SUSY}}^2} \times \tan \beta$$

SUSY corrections at 1L:

$$a_\mu^{\text{SUSY},1\text{L}} \approx 13 \times 10^{-10} \left(\frac{100 \text{ GeV}}{M_{\text{SUSY}}} \right)^2 \tan \beta \text{ sign}(\mu)$$

$M_{\text{SUSY}} (= m_{\tilde{\mu}} = m_{\tilde{\nu}} = m_{\tilde{\chi}})$: generic SUSY mass scale

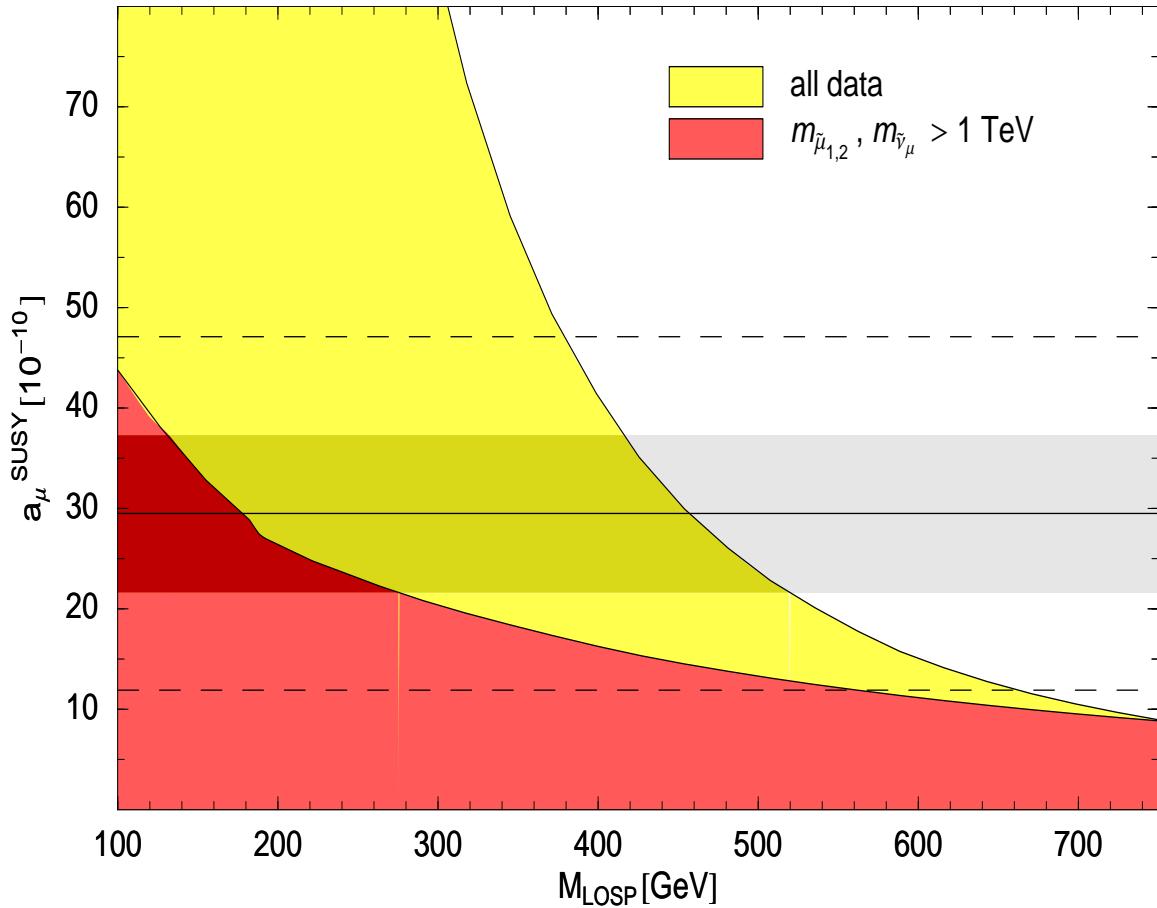
$$a_\mu^{\text{SUSY},1\text{L}} = (-100 \dots + 100) \times 10^{-10}$$

$$a_\mu^{\text{exp}} - a_\mu^{\text{theo,SM}} \approx (28 \pm 8) \times 10^{-10}$$

⇒ SUSY could easily explain the “discrepancy”

⇒ a_μ can provide bounds on SUSY parameter space
(by requiring agreement at the 95% C.L.)

Example: Scan over SUSY parameter space



Scan over
 $\mu, M_2, m_{\tilde{\mu}}, A_\mu$
LOSP = lightest observable
SUSY particle
LOSP = $\tilde{\mu}$ or $\tilde{\chi}$
[D. Stöckinger '06]

SUSY could easily explain
discrepancy

Alternatives to SUSY?

Generic BSM physics at M_{NP} :

$$a_\mu^{\text{NP}} \sim 1 \times 10^{-10} \left(\frac{300 \text{ GeV}}{M_{\text{NP}}} \right)^2$$

⇒ much too small!

Two advantages of SUSY:

- $\tan \beta$ -enhancement
- low SUSY masses possible

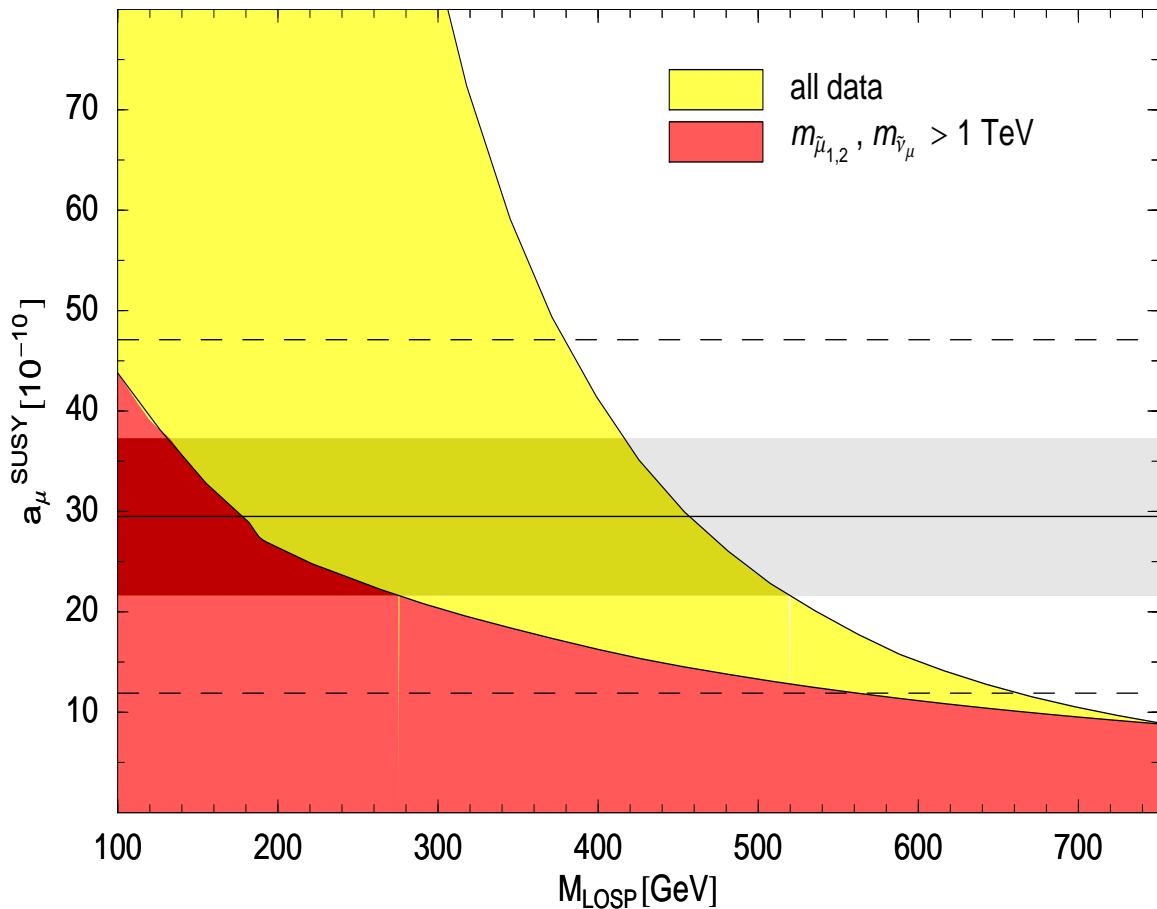
Future expectations:

- **Experiment:**
New BNL experiment proposed
see e.g. [*L. Roberts, D. Stöckinger et al. '07*]
reduction of experimental error by 2
- **Theory:**
Improvement in **light-by-light**?
Improvement from new e^+e^- data!

Overall improvement:

$$8 \times 10^{-10} \Rightarrow 4 \times 10^{-10}$$

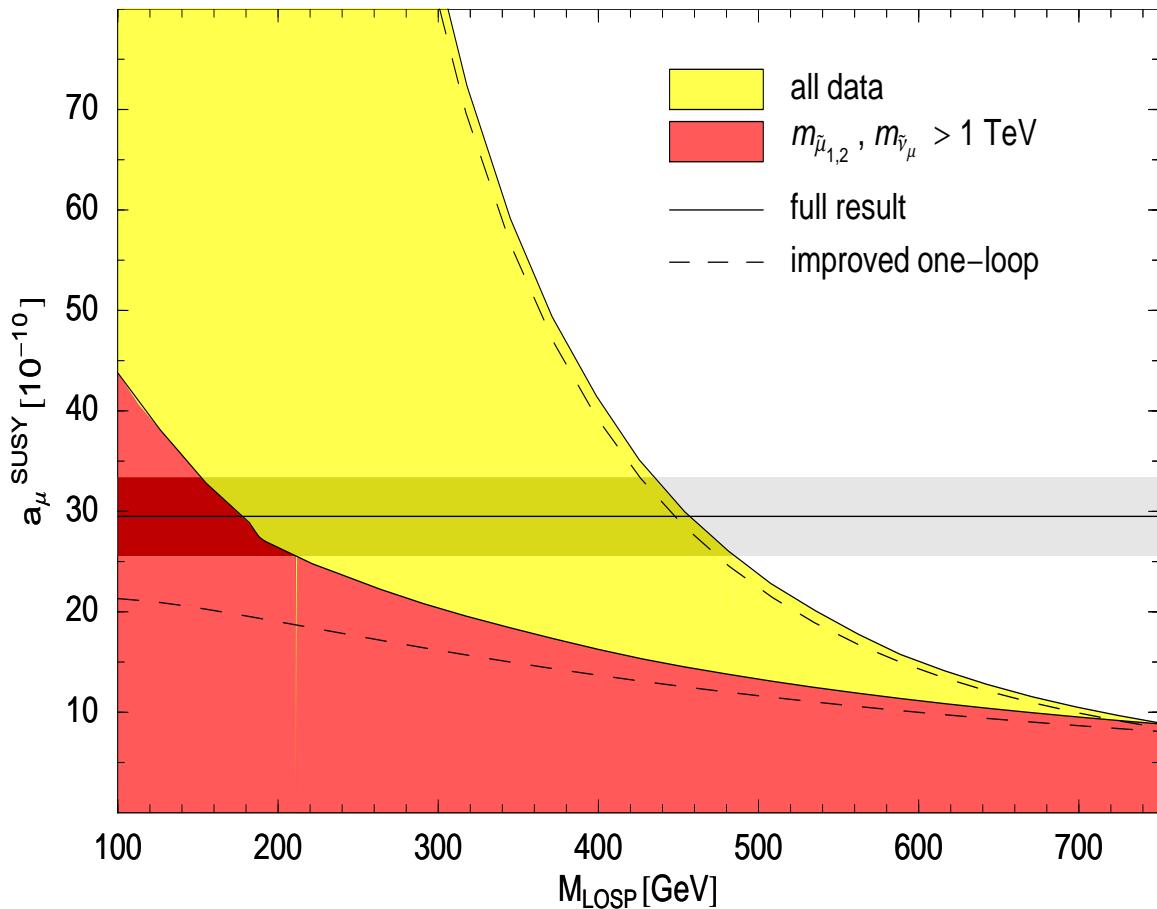
Old example: Scan over SUSY parameter space



Scan over
 $\mu, M_2, m_{\tilde{\mu}}, A_\mu$
LOSP = lightest observable
SUSY particle
LOSP = $\tilde{\mu}$ or $\tilde{\chi}$
[D. Stöckinger '06]

SUSY could easily explain
discrepancy

New example: Scan over SUSY parameter space



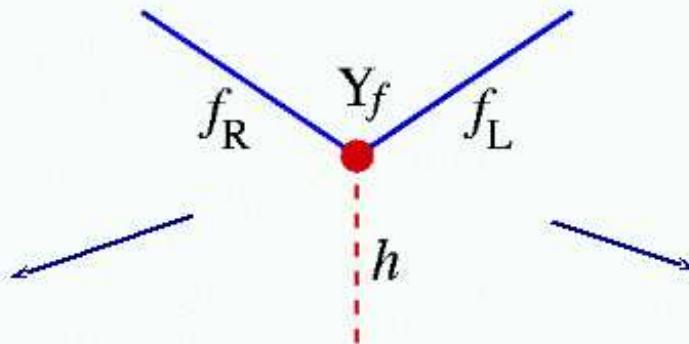
Scan over
 $\mu, M_2, m_{\tilde{\mu}}, A_\mu$
LOSP = lightest observable
SUSY particle
LOSP = $\tilde{\mu}$ or $\tilde{\chi}$
[D. Stöckinger '06]

SUSY could easily explain
discrepancy

With improved precision (and similar central value):
⇒ strong bounds on the MSSM parameter space

3. Electric dipole moments

Motivation: CPV in the SM



$$\sin(\delta_{KM}) \propto \text{Det}[Y_u Y_u^\dagger, Y_d Y_d^\dagger]$$

$$\bar{\theta}_{QCD} \sim \text{Arg Det}[Y_u Y_d]$$

(in a convenient basis)

- Experimentally $\delta_{KM} \sim O(1)$, and consistently explains CP-violation in K and B meson mixing and decays
- Experimentally, $\theta < 10^{-9}$! (strong CP problem)

Do we anticipate/expect other CPV sources?

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Yes!

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Yes!

- Baryogenesis requires extra CPV
- most “UV completions” of the SM (e.g. the MSSM) provide additional sources of CPV

Within the SM: CPV is “hidden” behind the flavor structure: [C. Jarlskog '85]

$$J_{CP} \sim 10^{-5} \sin \delta_{CKM}$$

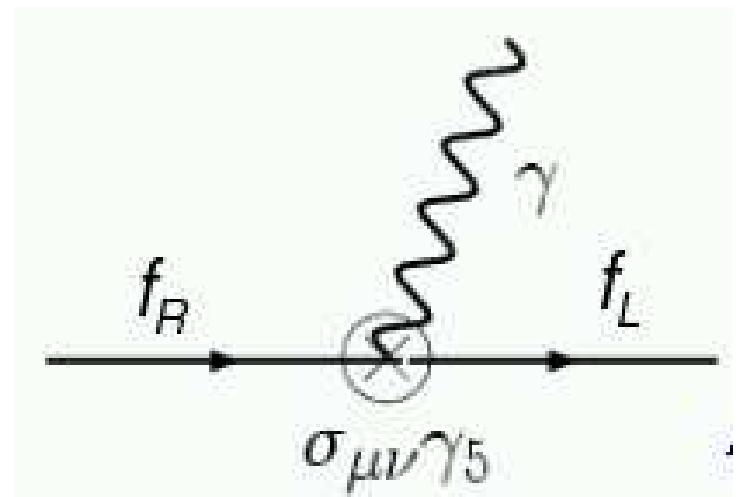
⇒ look for CPV in flavor diagonal channels
(i.e. with small SM background)

sensitivity through

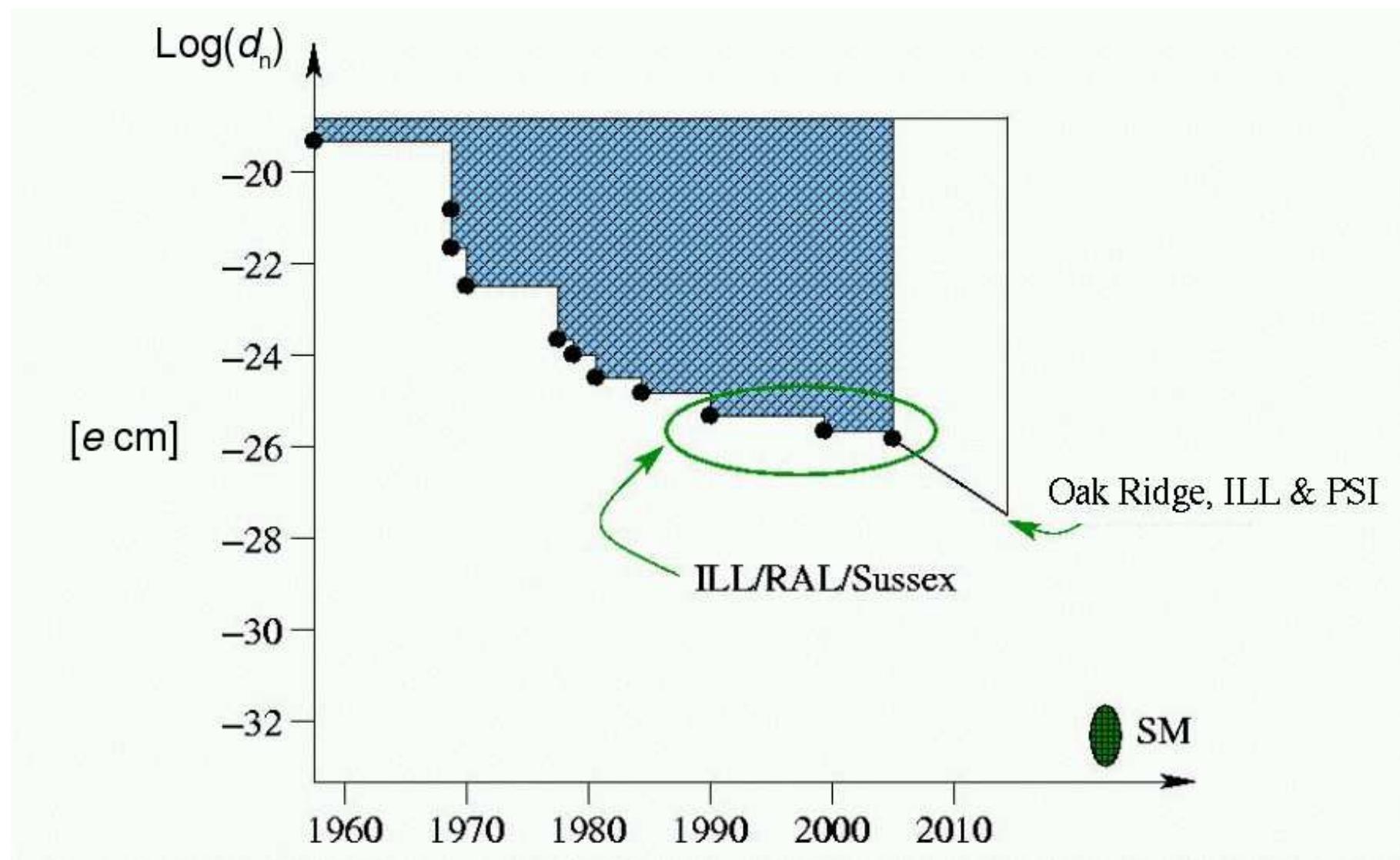
EDMs of electron, neutron, deuteron, ...

Current experimental limits:

EDMs vanish with very high precision ⇒ strong constraints on new physics



Example: EDM of the neutron



⇒ constant progress over recent years in various experiments

Current experimental progress:

1. Hg EDM experiment (Seattle)

factor of 2 improvement on d_e expected soon

2. YbF experiment (Imperial London)

results on d_e in a few years . . .

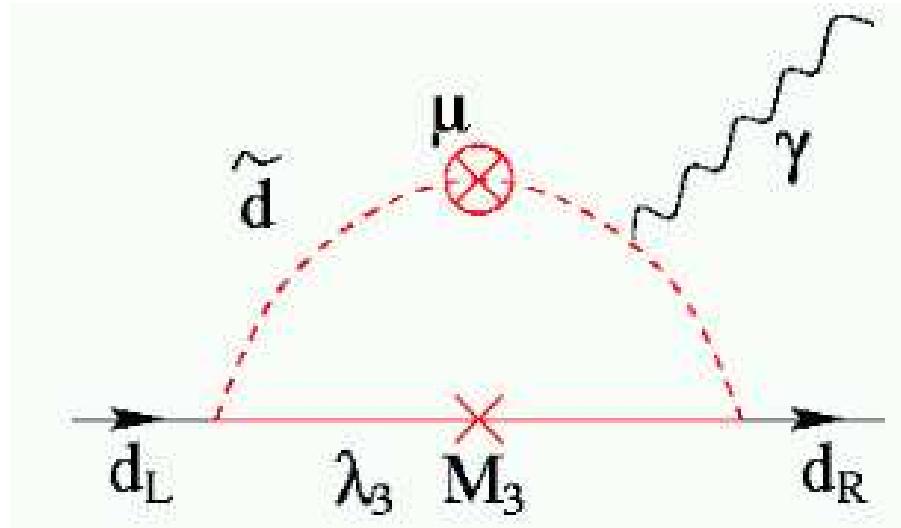
3. deuteron EDM experiment (BNL)

results in a few years . . .

4. more on larger time scales . . .

Implications for SUSY:

“Generic” SUSY contribution to EDM:



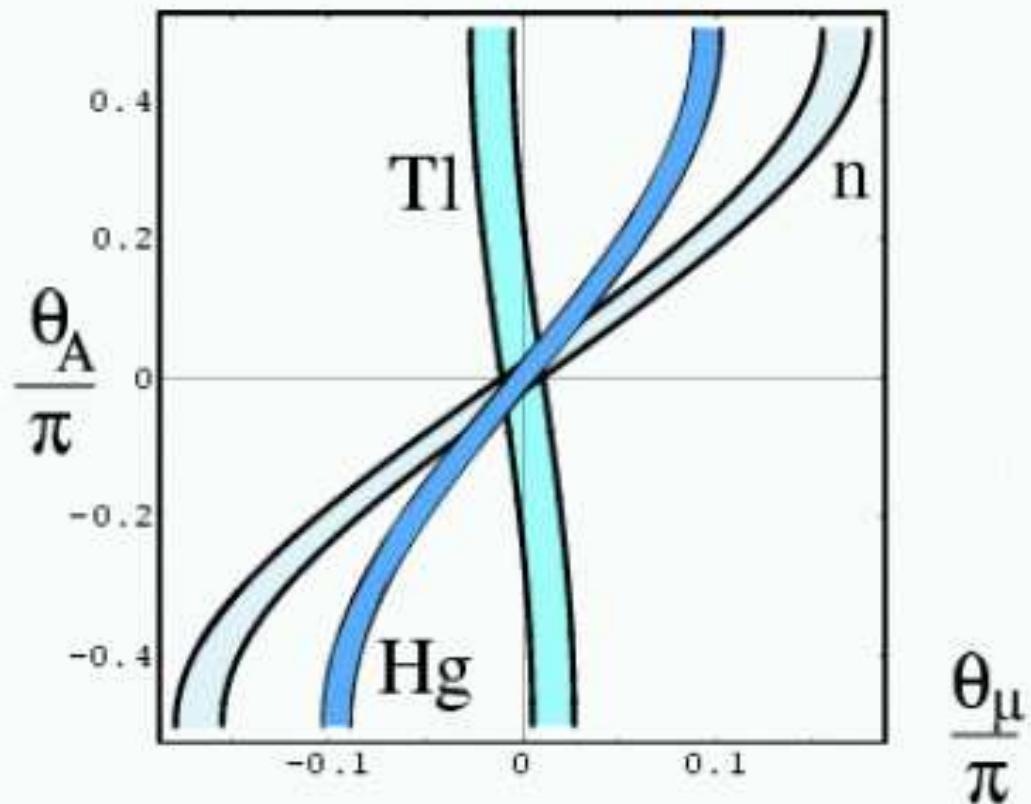
$$\Rightarrow \frac{d_n}{m_d} \sim \frac{1}{16\pi^2} \frac{\mu m_{\tilde{g}}}{M_{\text{SUSY}}} \sin \theta_\mu$$

[Ellis, Ferrara, Nanopoulos '82]

⇒ SUSY CP “problem”:

Most CPV phases
must be:
 $\mathcal{O}(10^{-2} - 10^{-3})$

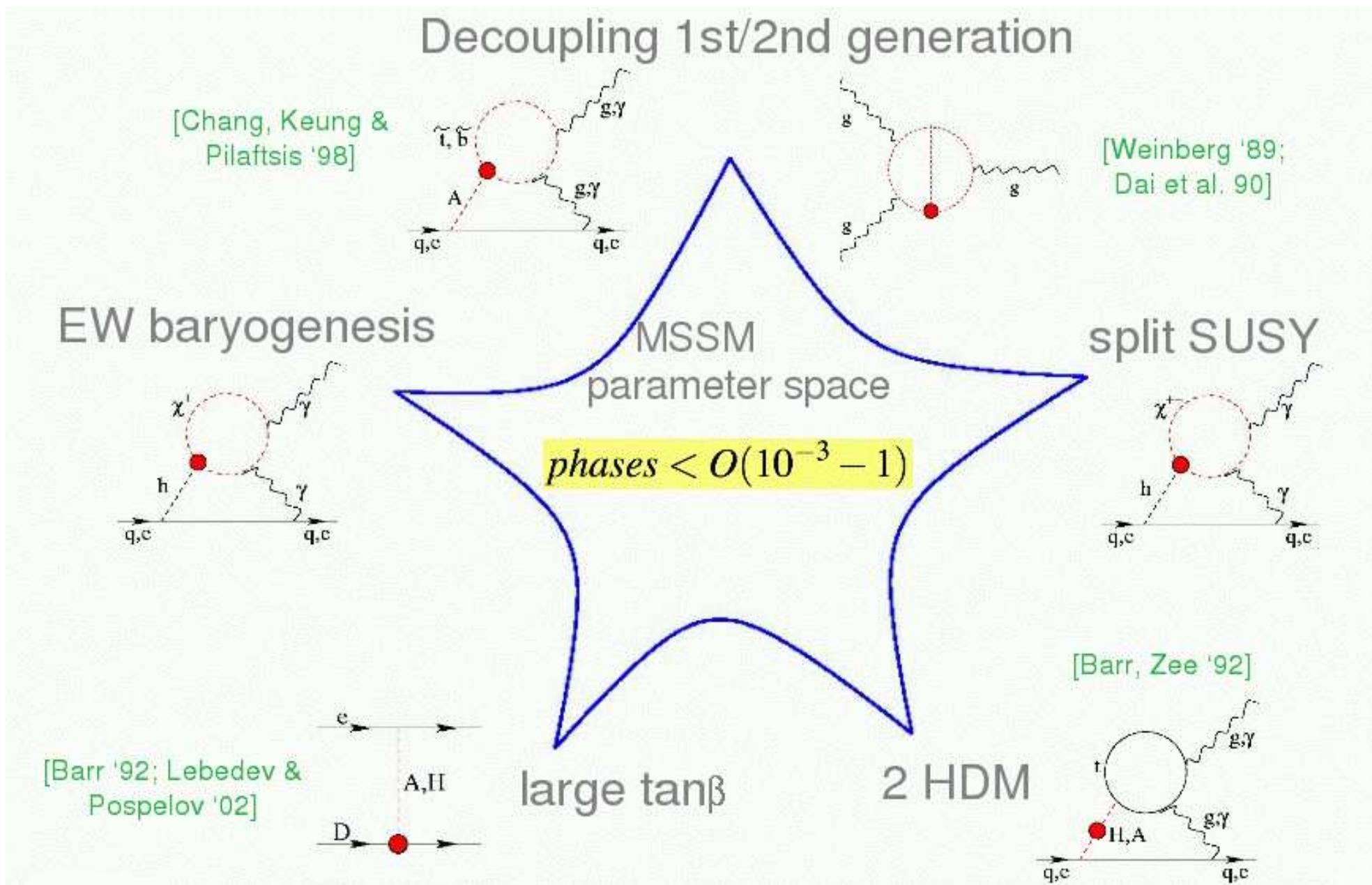
especially: $\theta_\mu + \theta_{M_2}$



$$M_{soft} = 500 \text{ GeV}$$

[K. Olive, M. Pospelov, A. Ritz, Y. Santoso '05]

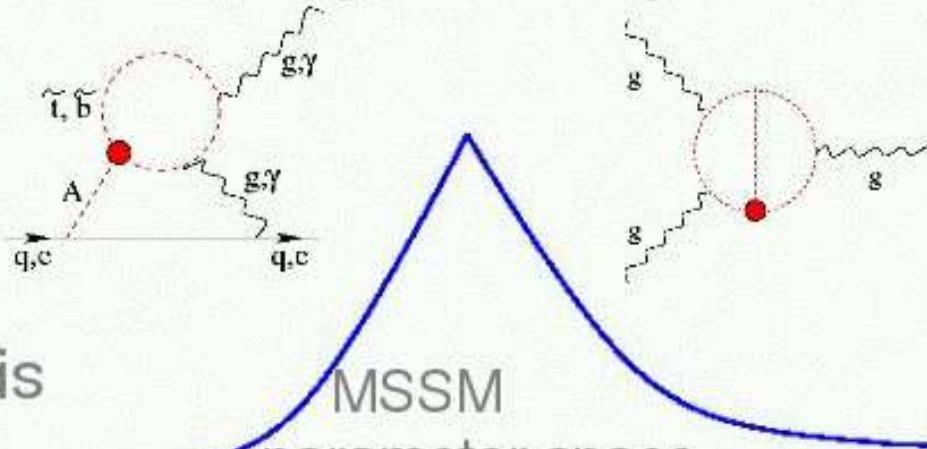
Overview about MSSM constraints:



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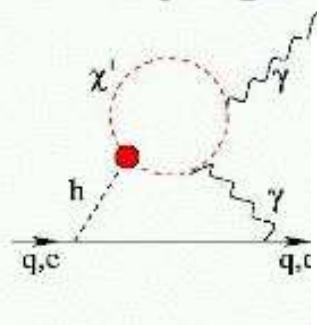
Decoupling 1st/2nd generation

[Chang, Keung & Pilaftsis '98]

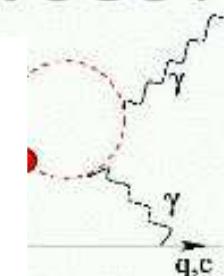


[Weinberg '89;
Dai et al. 90]

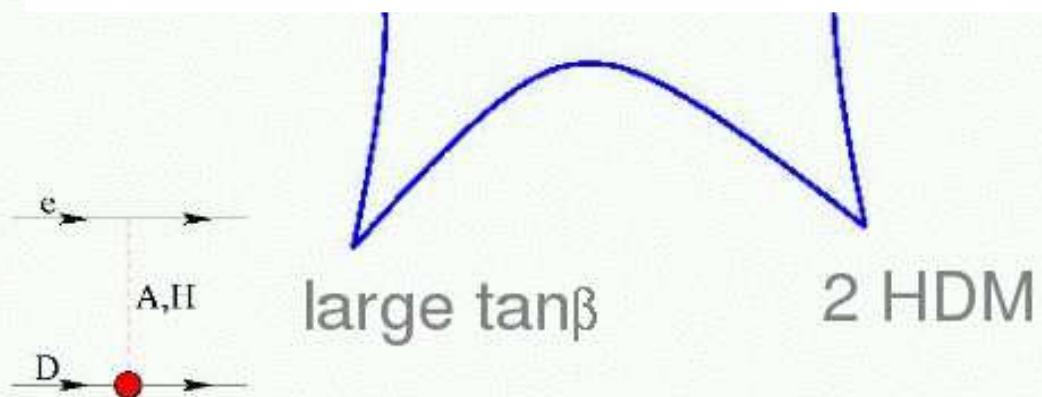
EW baryogenesis



Have to be taken
into account in any
phenomenological analysis!



[Barr '92; Lebedev & Pospelov '02]



[Barr, Zee '92]



4. Electroweak Precision Observables in the SM

1.) M_W :

Theoretical prediction for M_W in terms of $M_Z, \alpha, G_\mu, \Delta r$:

$$M_W^2 \left(1 - \frac{M_W^2}{M_Z^2} \right) = \frac{\pi \alpha}{\sqrt{2} G_\mu} (1 + \Delta r)$$

\Updownarrow
loop corrections

Evaluate Δr from μ decay $\Rightarrow M_W$

One-loop result for M_W in the SM:

[A. Sirlin '80] , [W. Marciano, A. Sirlin '80]

$$\begin{aligned} \Delta r_{\text{1-loop}} &= \Delta \alpha - \frac{c_W^2}{s_W^2} \Delta \rho + \Delta r_{\text{rem}}(M_H) \\ &\sim \log \frac{M_Z}{m_f} \quad \sim m_t^2 \quad \sim \log(M_H/M_W) \\ &\sim 6\% \quad \sim 3.3\% \quad \sim 1\% \end{aligned}$$

Status of M_W calculation in the SM

- $\Delta r: \mathcal{O}(\alpha^2)$: full electroweak two-loop results
[A. Freitas, W. Hollik, W. Walter, G. Weiglein '03]
[M. Awramik, M. Czakon '04] [Onishenko, Veretin '04]
- $\Delta\rho: \mathcal{O}(\alpha\alpha_s^2)$: leading three-loop contributions
[K. Chetyrkin, J Kühn, M. Steinhauser '95] [L. Avdeev et al. '95]
- $\Delta\rho: \mathcal{O}(\alpha^2\alpha_s), \mathcal{O}(\alpha^3)$: limit of $M_H \rightarrow 0$
[J. Van der Bij, K. Chetyrkin, M. Faisst, G. Jikia, T. Seidensticker '01]
- $\Delta\rho: \mathcal{O}(\alpha^2\alpha_s), \mathcal{O}(\alpha^3)$: limits with $M_H \neq 0$
[M. Faisst, J. Kühn, T. Seidensticker, O. Veretin '03]
- $\Delta\rho: \mathcal{O}(\alpha\alpha_s^3)$: various four-loop contributions
[Y. Schröder, M. Steinhauser '05]
[K. Chetyrkin, M. Faisst, J. Kühn, P. Maierhoefer, C. Sturm '06]
[R. Boughezal, M. Czakon '06]

Estimate of remaining higher-order uncertainties:

$$\delta M_W^{\text{theo}} = 4 \text{ MeV}$$

⇒ extremely remarkable precision

Comparison of SM prediction of M_W with direct measurements:

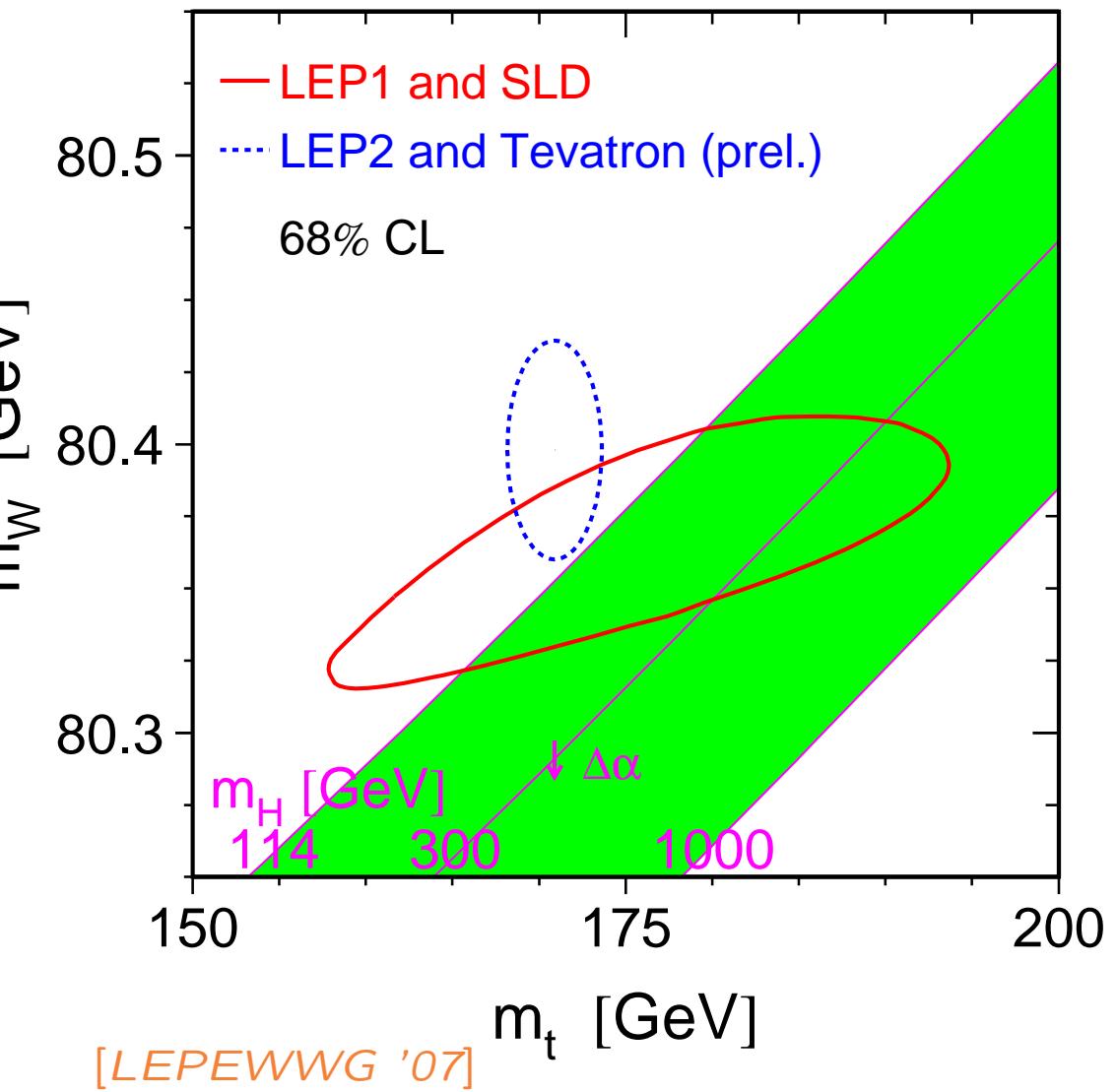
$$\Delta r = -\frac{11g_2^2}{96\pi^2} \frac{s_W^2}{c_W^2} \log\left(\frac{M_H}{M_W}\right)$$

general for EWPO:

$$\Delta \sim g_2^2 \left[\log\left(\frac{M_H}{M_W}\right) + g_2^2 \frac{M_H^2}{M_W^2} \right]$$

leading term: $\log(M_H)$

first term $\sim M_H^2$ with g_2^4



⇒ light Higgs boson preferred

More electroweak precision observables [LEPEWWG '05/'07]

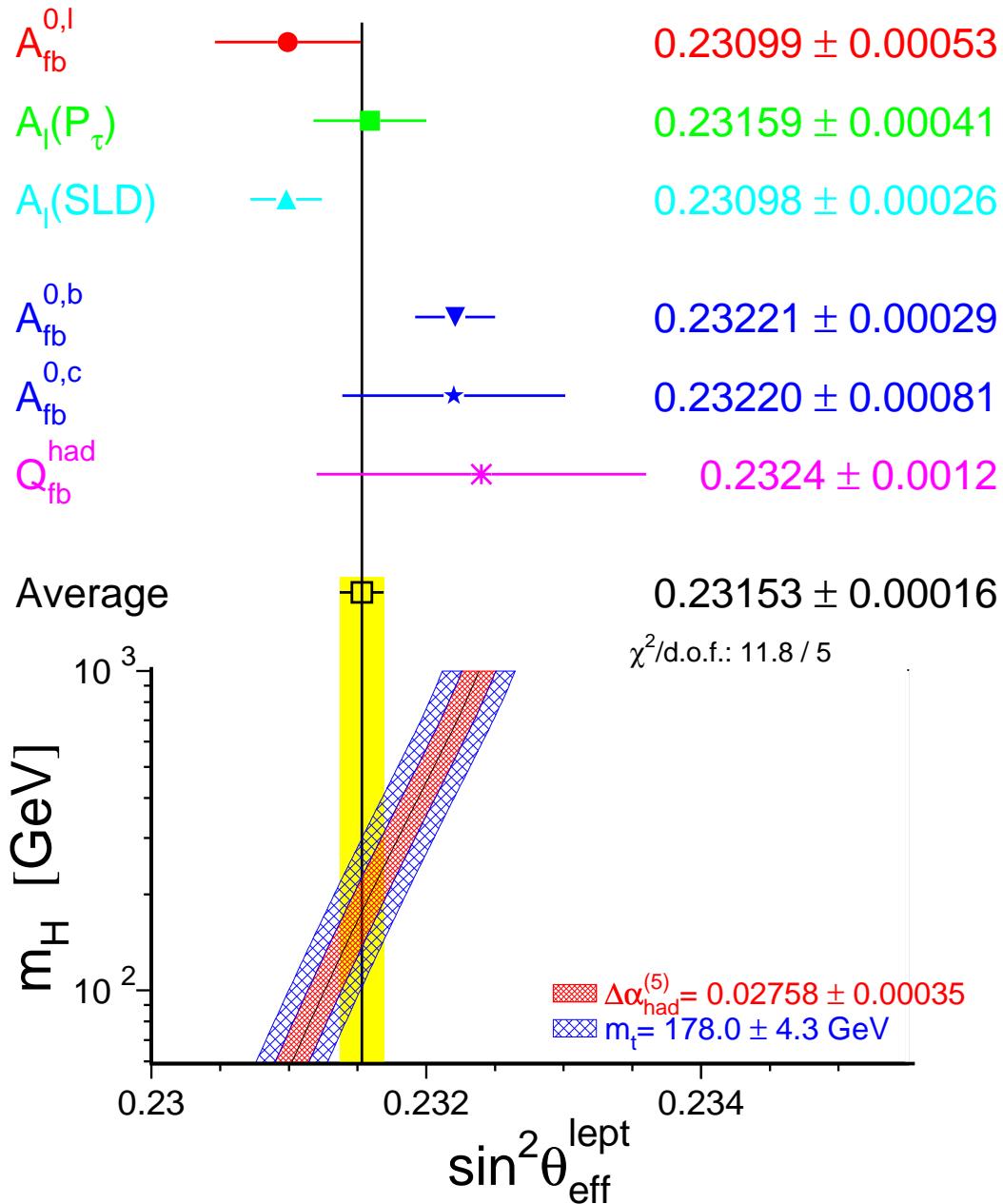
2.) Effective weak leptonic mixing angle $\sin^2 \theta_{\text{eff}}$:

$$\sin^2 \theta_{\text{eff}} = \frac{1}{4 |Q_f|} \left(1 - \text{Re} \frac{g_V^f}{g_A^f} \right)$$

Higher order contributions:

$$g_V^f \rightarrow g_V^f + \Delta g_V^f$$

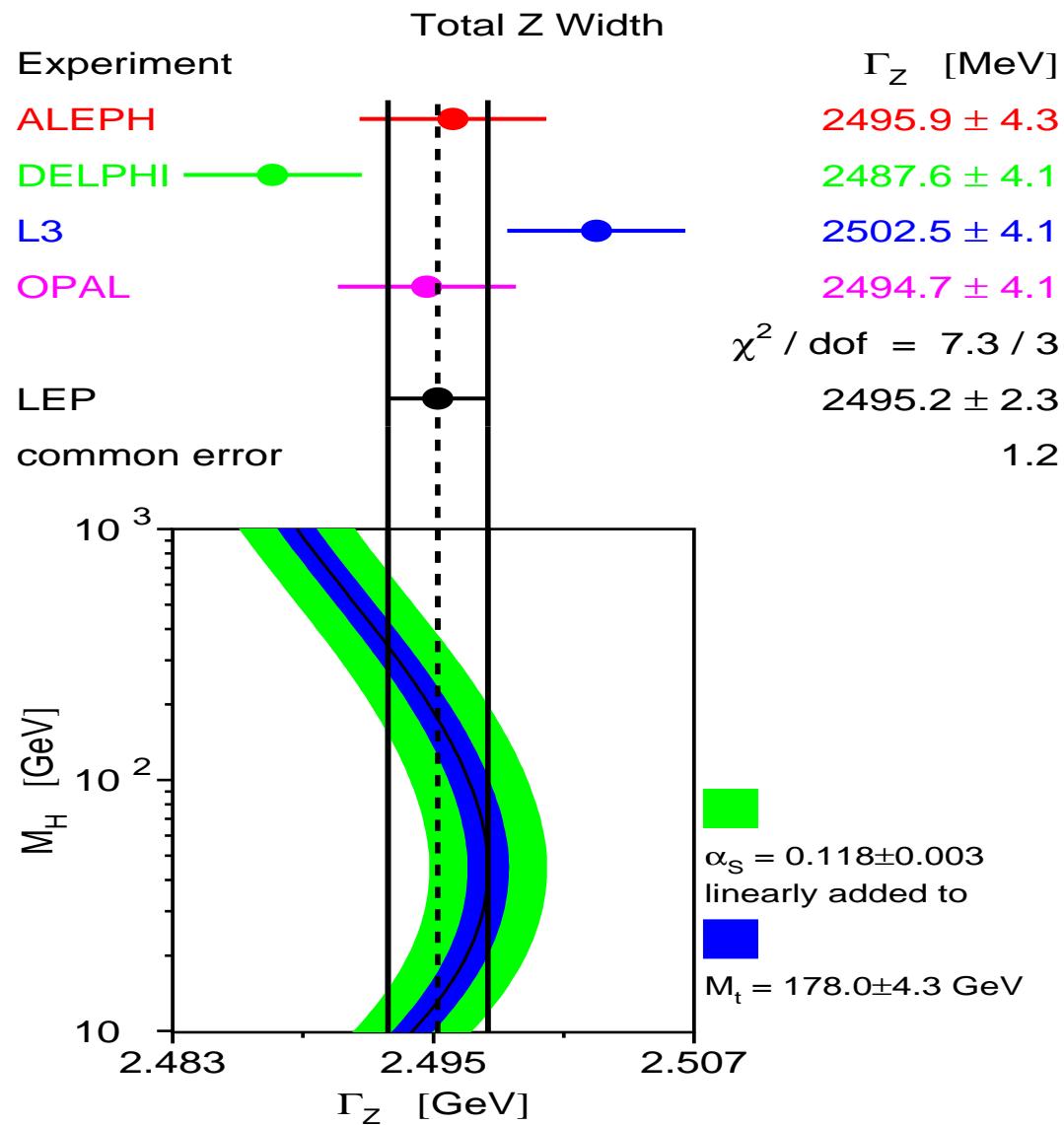
$$g_A^f \rightarrow g_A^f + \Delta g_A^f$$



3.) Total Z width Γ_Z :

$$\Gamma_Z = \sum_X \Gamma(Z \rightarrow X\bar{X})$$

including higher-order corrections



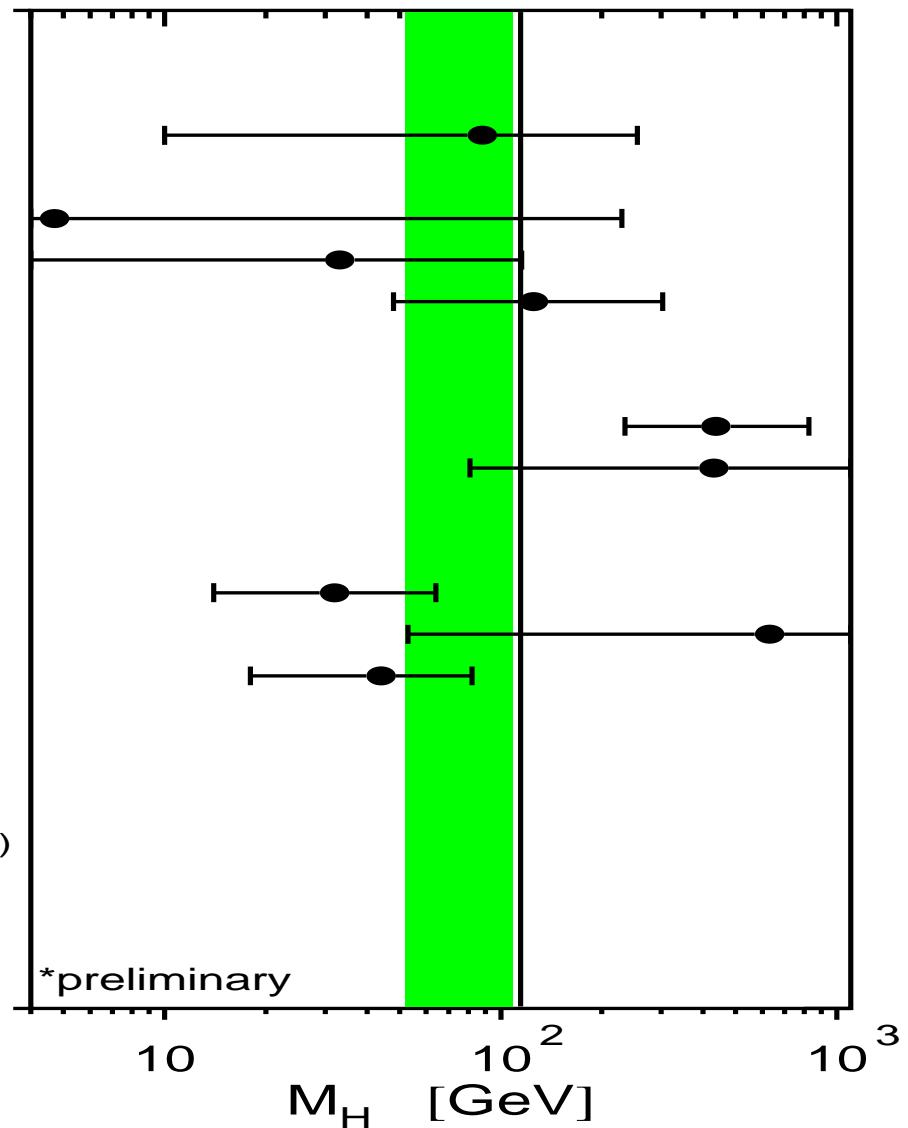
Results for M_H from other EWPO:

light Higgs preferred by:
 M_W , A_l^{LR} (SLD)

heavier Higgs preferred by:
 A_b^{FB} (LEP)
 \Rightarrow keeps SM alive

Γ_Z
 σ_{had}^0
 R_I^0
 $A_{\text{fb}}^{0,I}$
 $A_I(P_\tau)$
 R_b^0
 R_c^0
 $A_{\text{fb}}^{0,b}$
 $A_{\text{fb}}^{0,c}$
 A_b
 A_c
 $A_I(\text{SLD})$
 $\sin^2 \theta_{\text{eff}}^{\text{lept}}(Q_{\text{fb}})$
 m_W^*
 Γ_W^*

 $Q_W(\text{Cs})$
 $\sin^2 \theta_{\overline{\text{MS}}}(\text{e}^- \text{e}^-)$
 $\sin^2 \theta_W(\nu N)$
 $g_L^2(\nu N)$
 $g_R^2(\nu N)$



\Rightarrow light Higgs boson preferred

[LEPEEWG '07]

Global fit to all SM data:

[LEPEWWG '07]

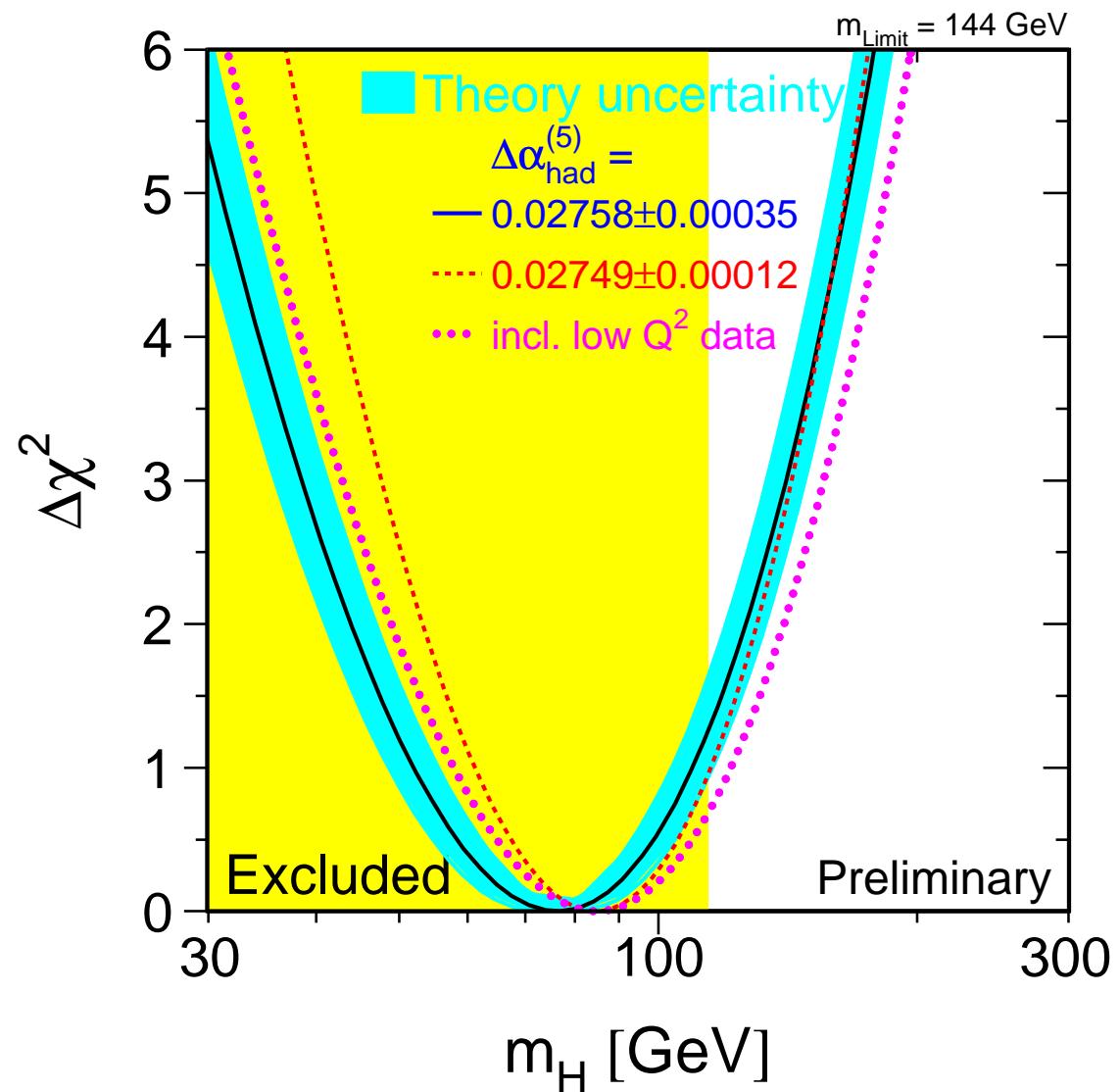
$$\Rightarrow M_H = 76^{+33}_{-24} \text{ GeV}$$

$M_H < 144 \text{ GeV}$, 95% C.L.

Assumption for the fit:

SM incl. Higgs boson

\Rightarrow no confirmation of
Higgs mechanism



\Rightarrow Higgs boson seems to be light, $M_H \lesssim 150 \text{ GeV}$

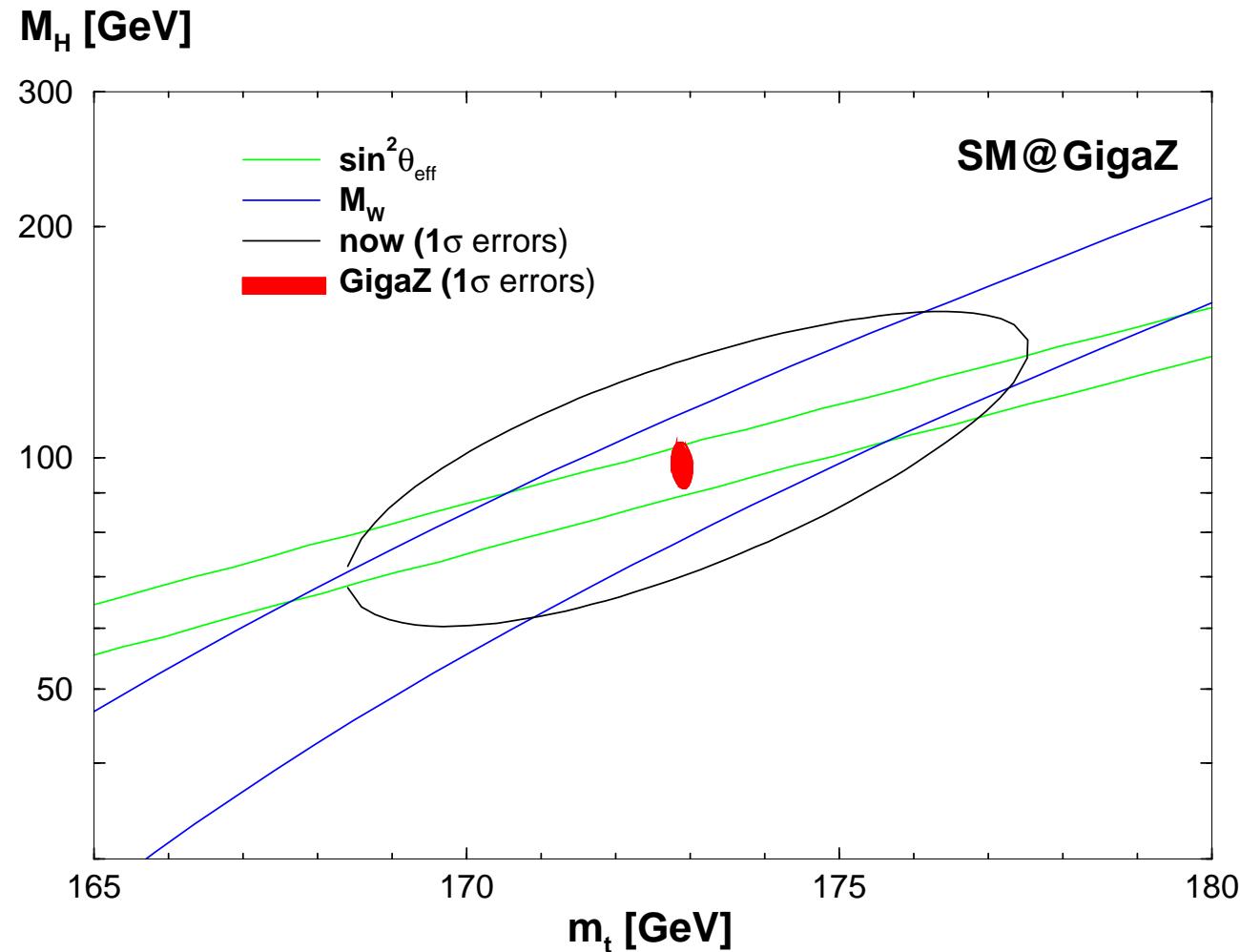
Future expectations:

	now	Tevatron	LHC	ILC	ILC with GigaZ
$\delta \sin^2 \theta_{\text{eff}} (\times 10^5)$	16	—	14–20	—	1.3
δM_W [MeV]	25	20	15	10	7
δm_t [GeV]	1.8	1.2	1.0	0.2	0.1
δM_h [MeV]	—	2000	200	50	50

⇒ Improvement in M_H determination?

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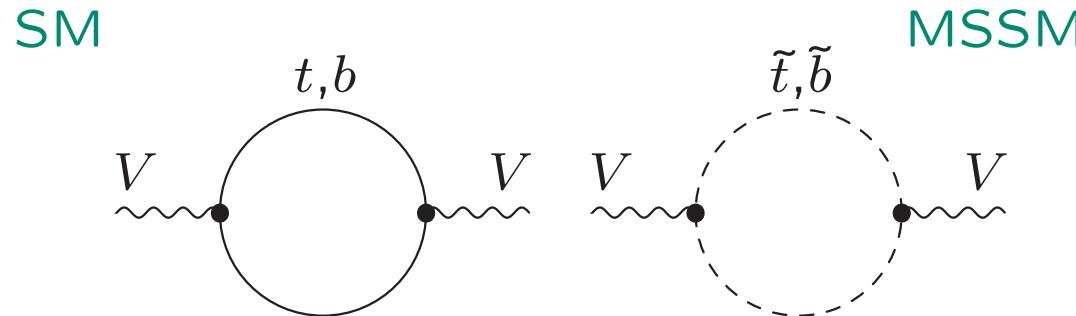
[J. Erler, S.H., W. Hollik, G. Weiglein, P. Zerwas '00]



5. Electroweak Precision Observables in the MSSM

Differences compared to the SM:

1.) New contributions from SUSY particles:



2.) CPV effects via new complex phases

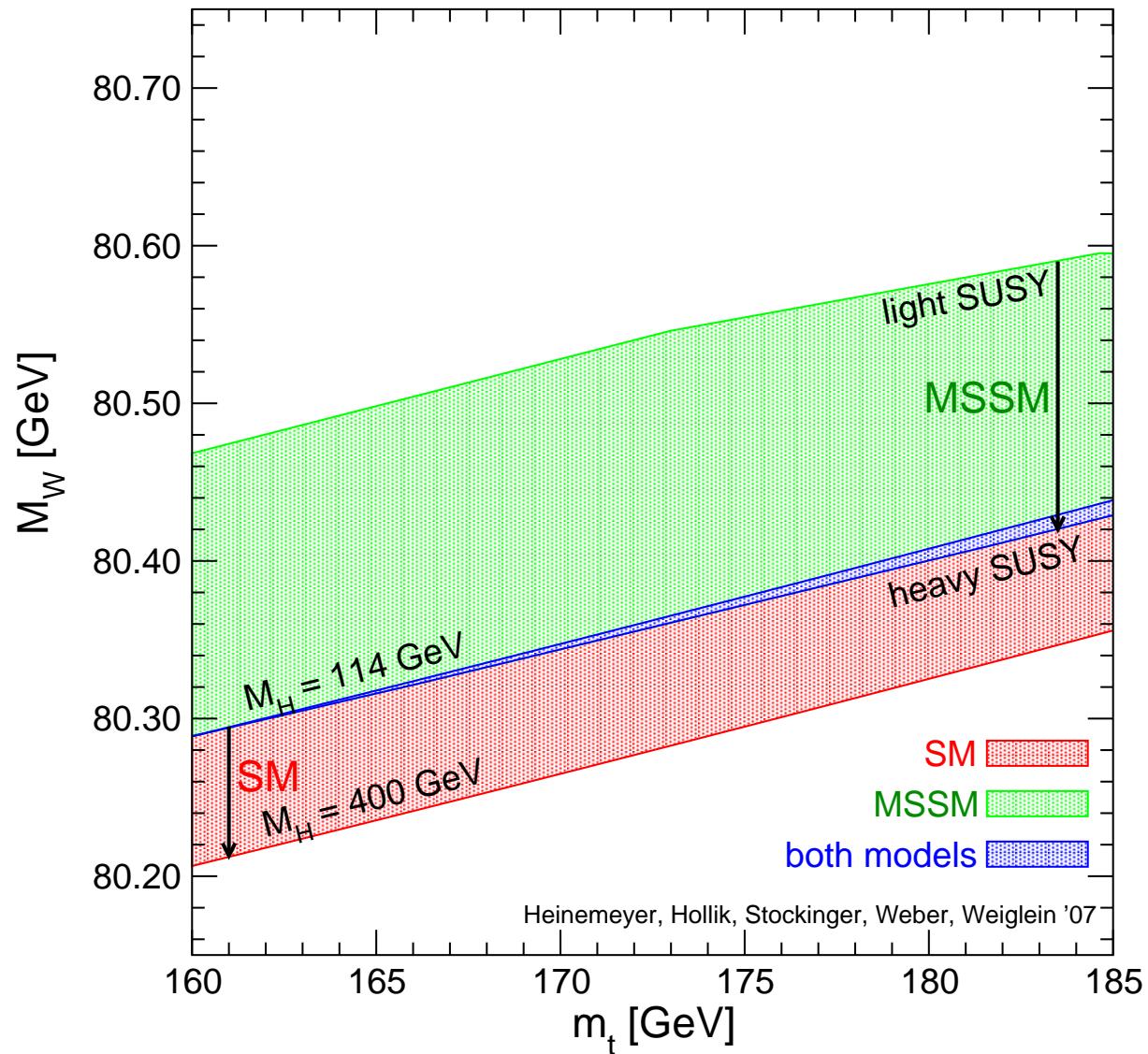
3.) large Yukawa corrections: $\sim m_t^4 \log \left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right)$

4.) large corrections from the b/\tilde{b} sector for large $\tan \beta$

5.) non-decoupling SUSY effects: $\sim \log \frac{M_{\text{SUSY}}}{M_W}$

Example: Prediction for M_W in the SM and the MSSM :

[S.H., W. Hollik, D. Stockinger, A.M. Weber, G. Weiglein '07]



MSSM band:

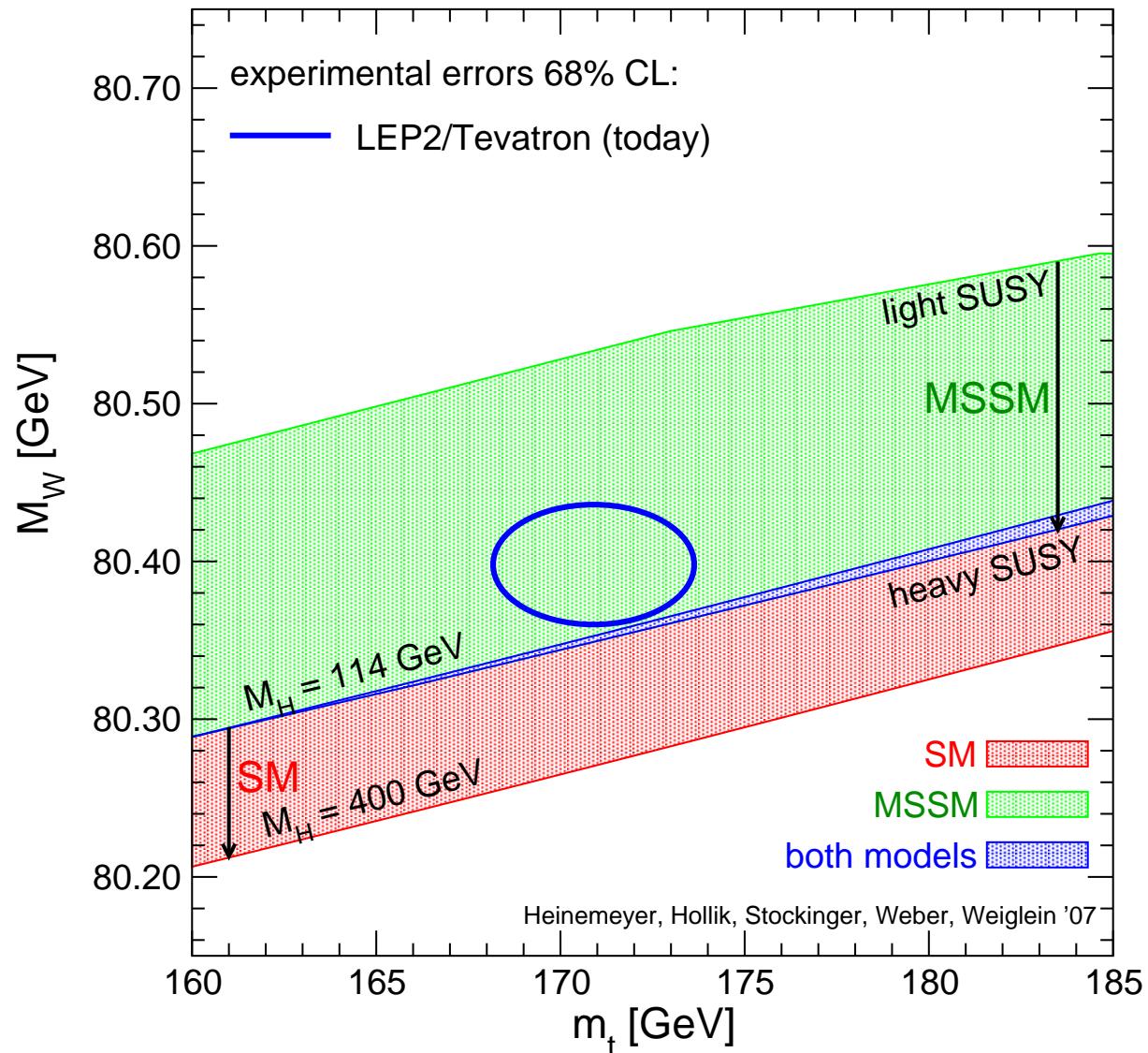
scan over
SUSY masses

overlap:
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SM band:
variation of M_H^{SM}

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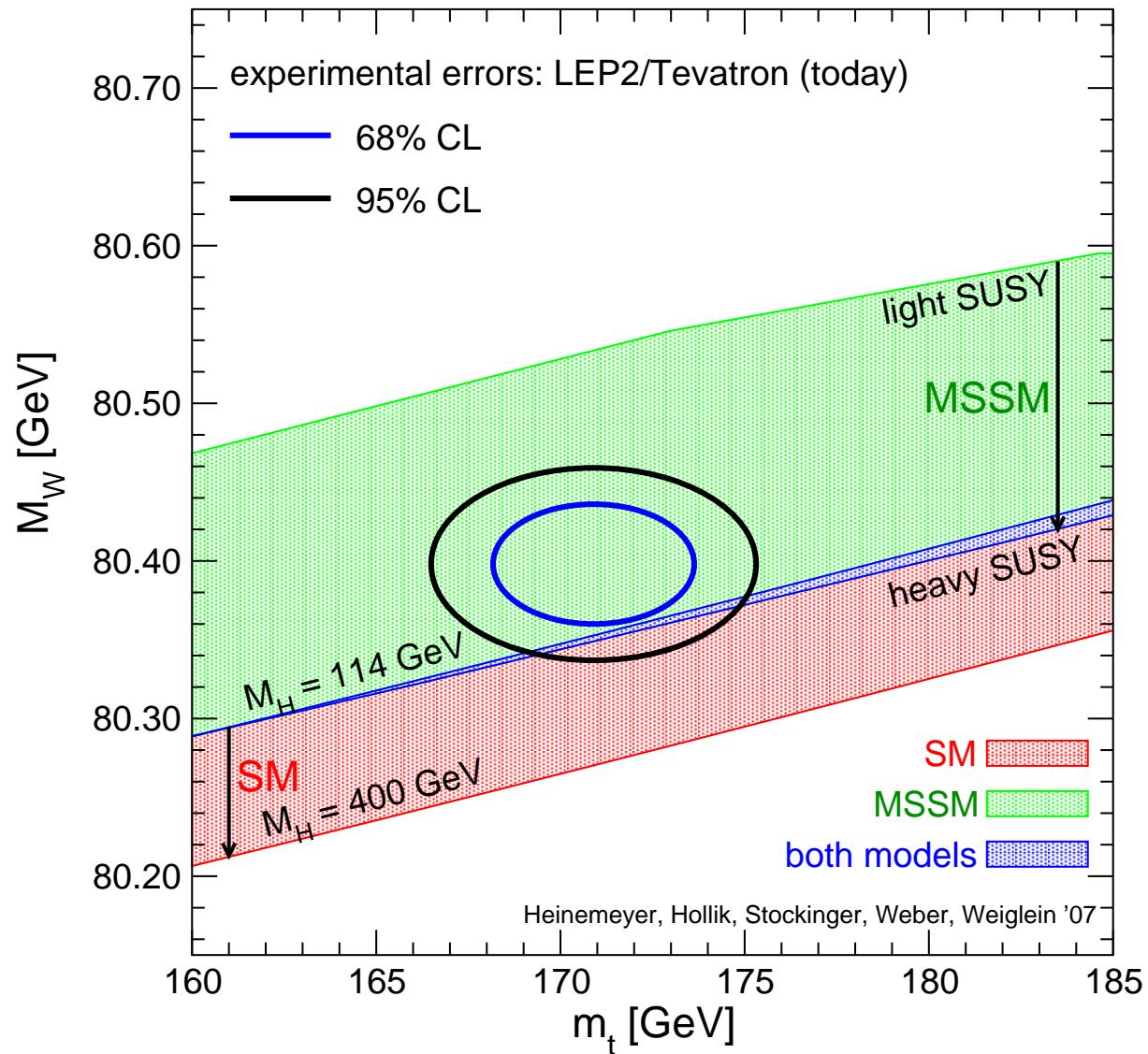
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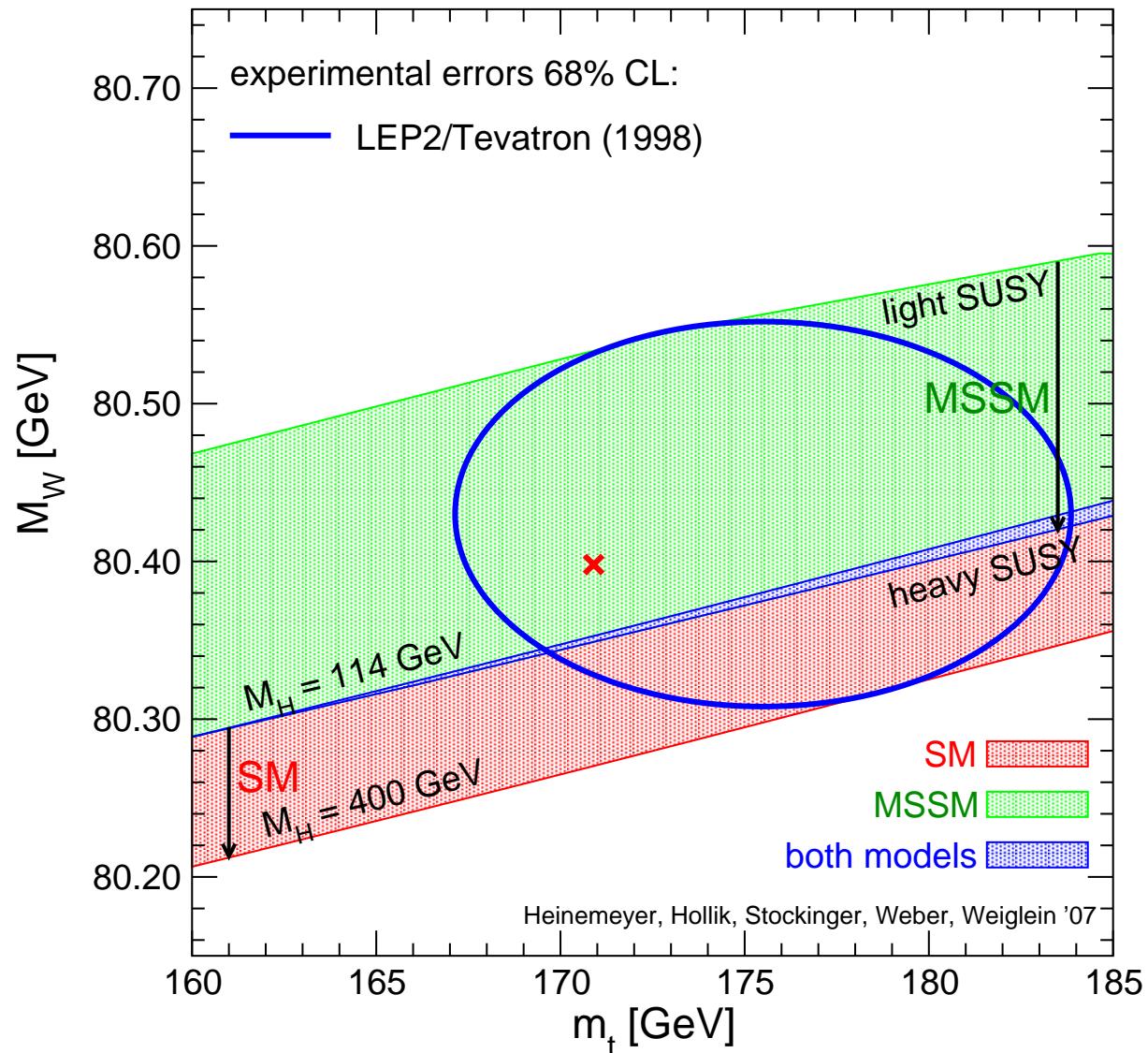
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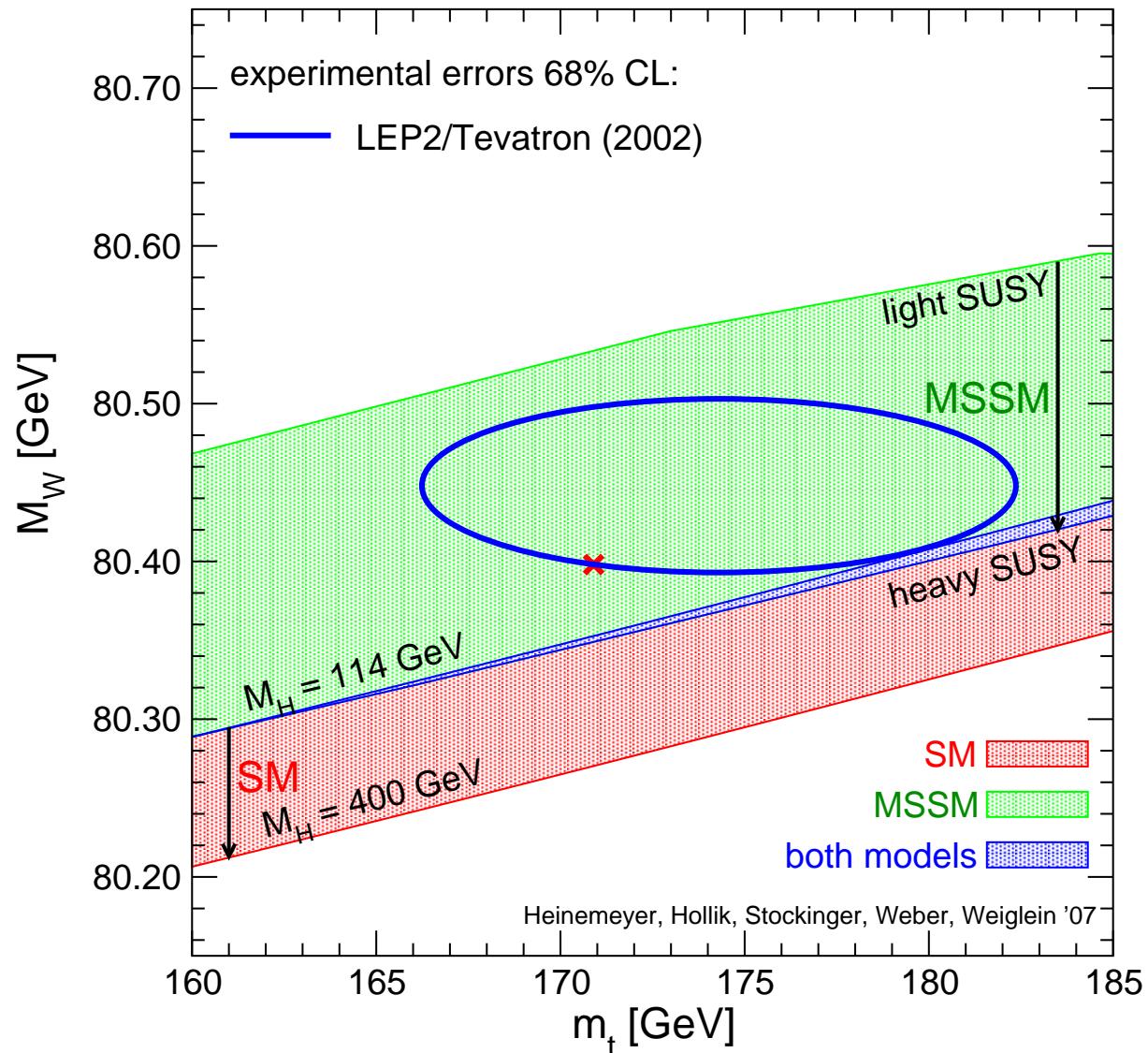
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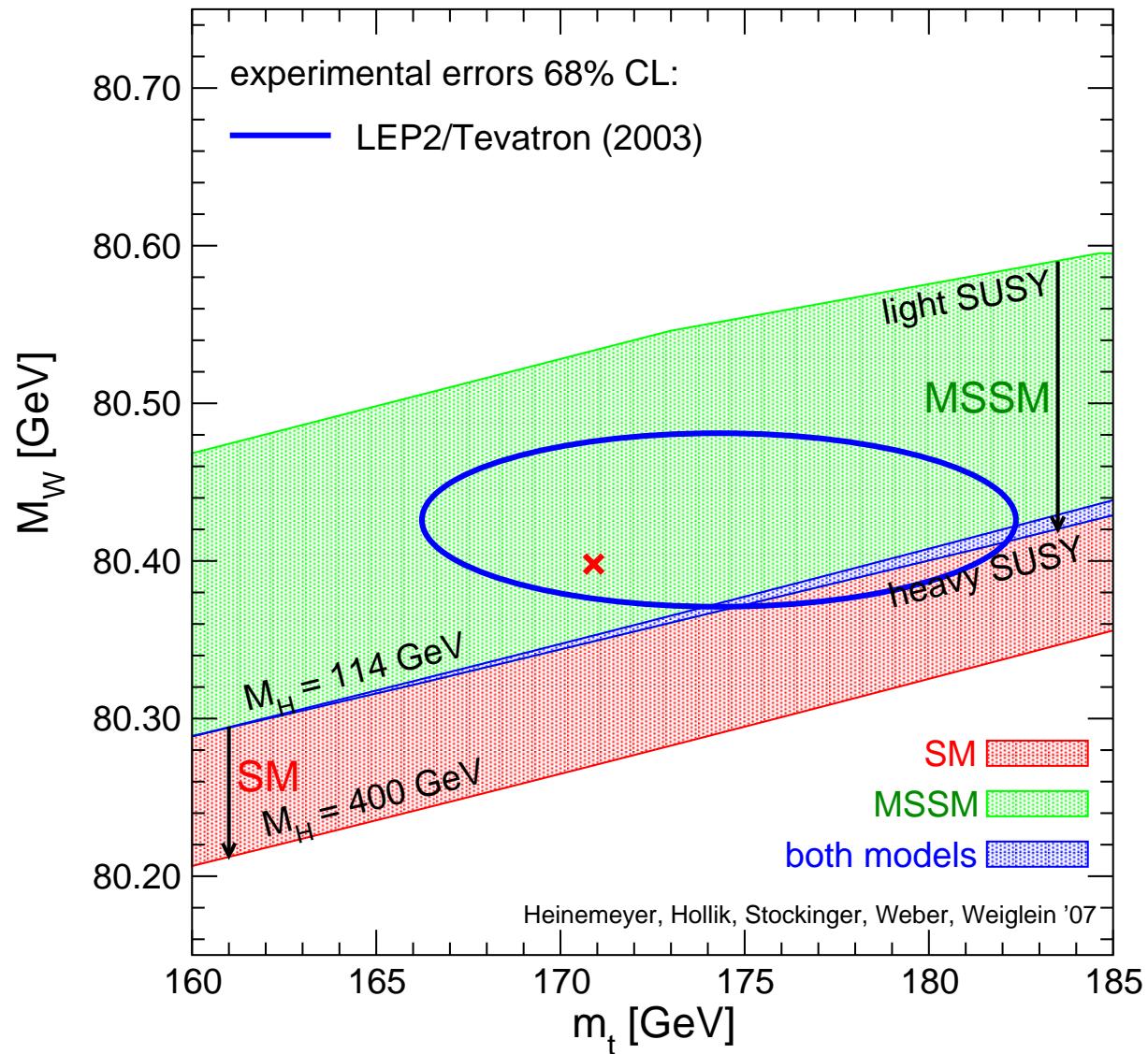
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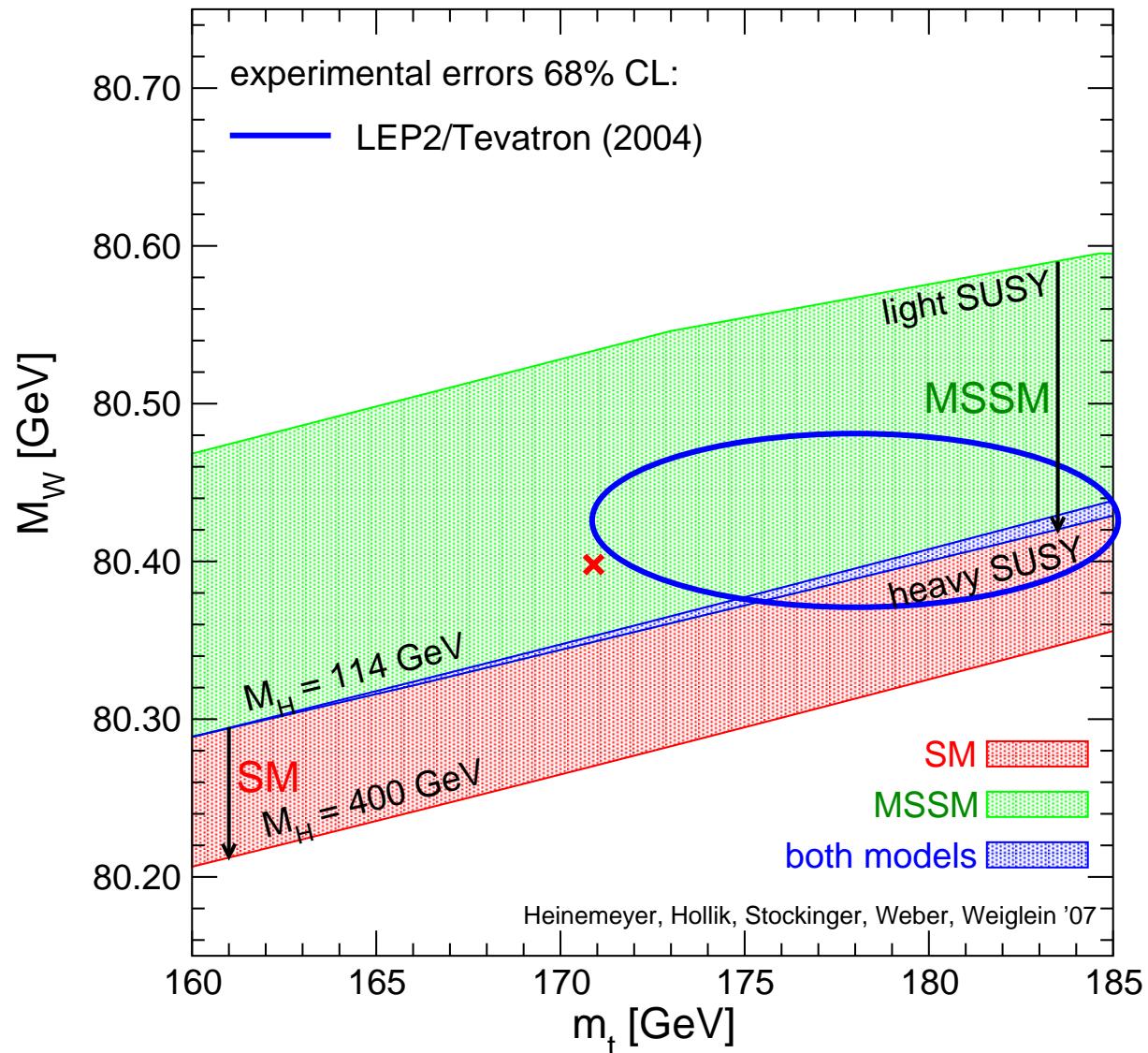
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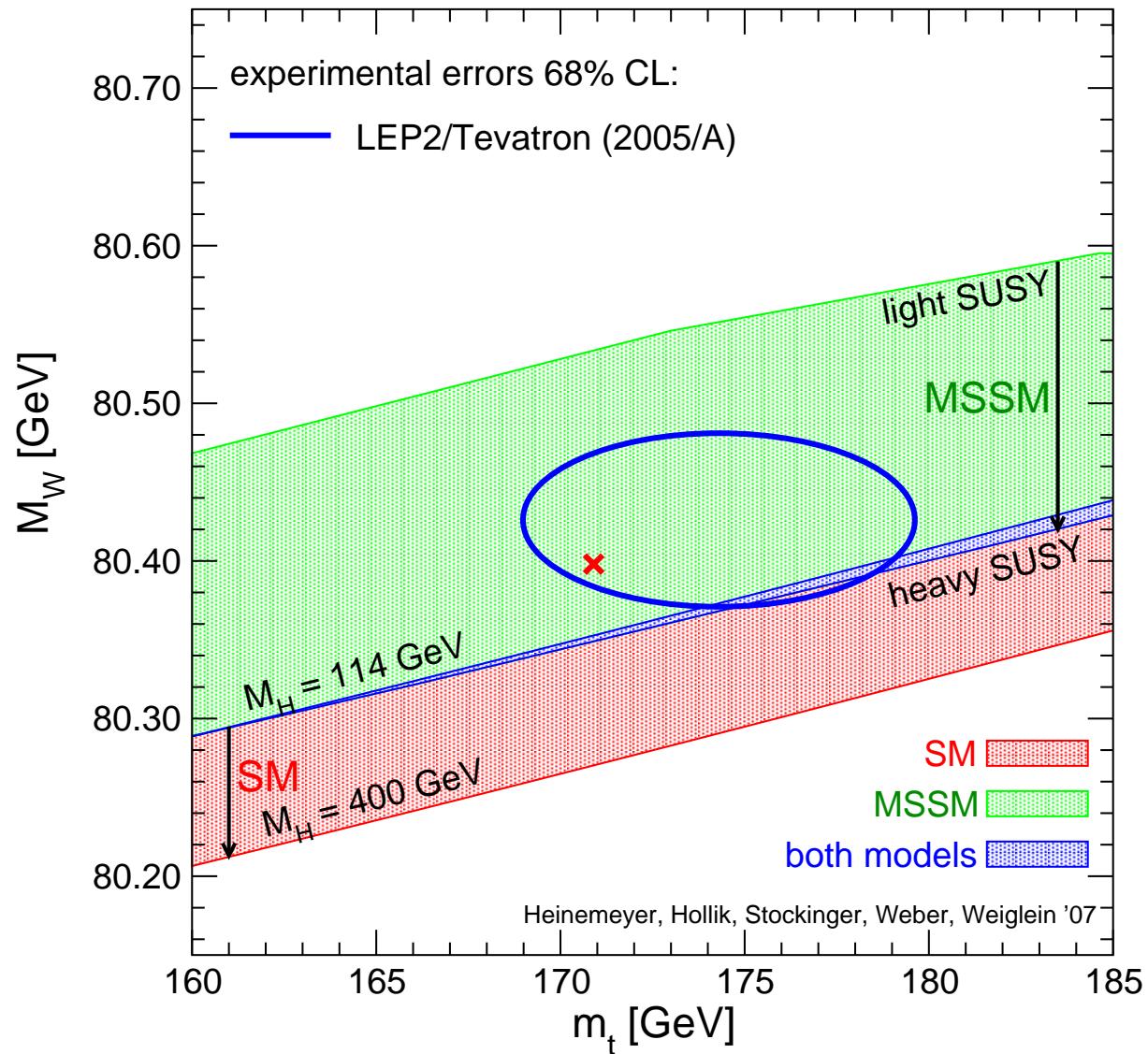
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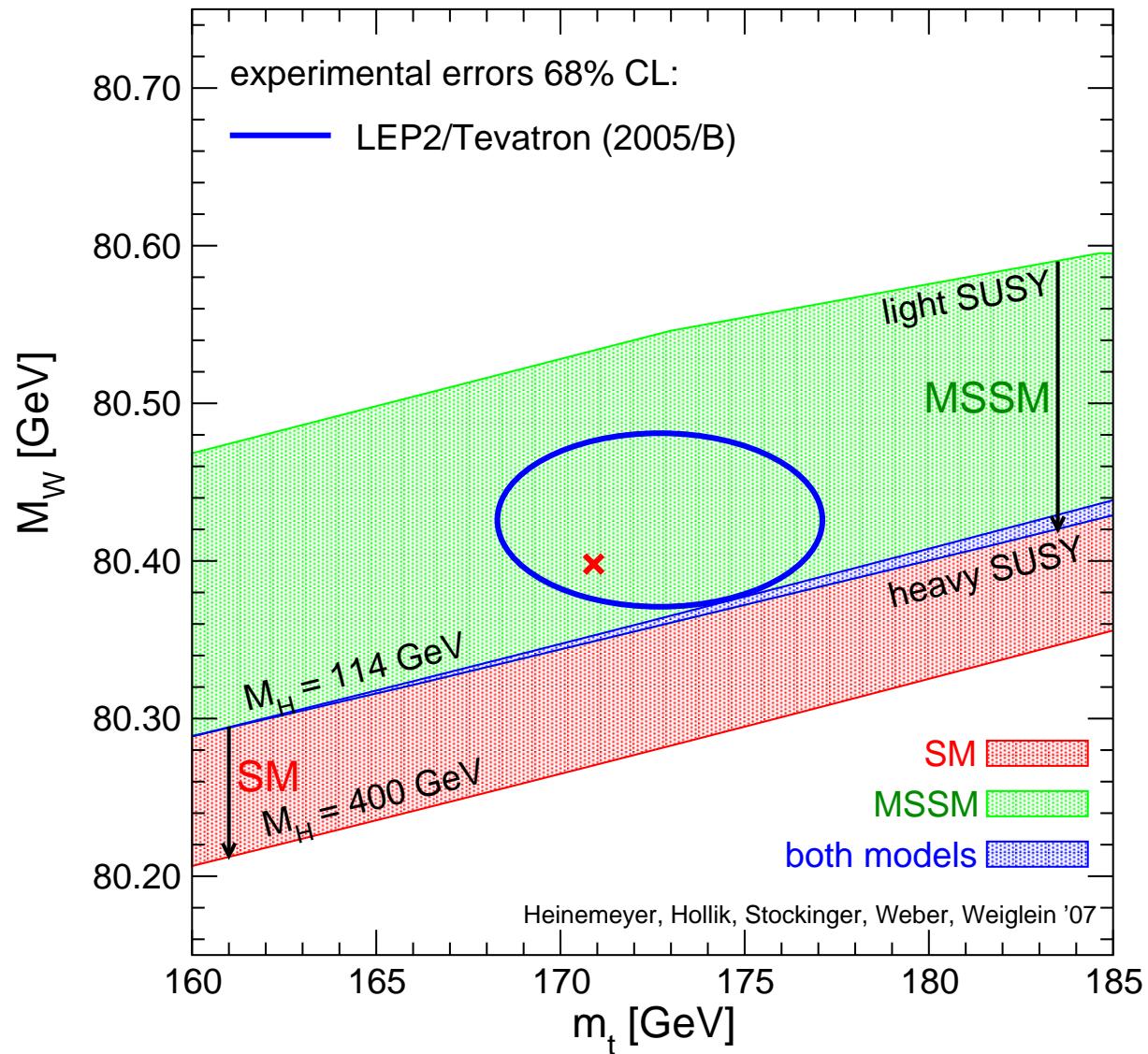
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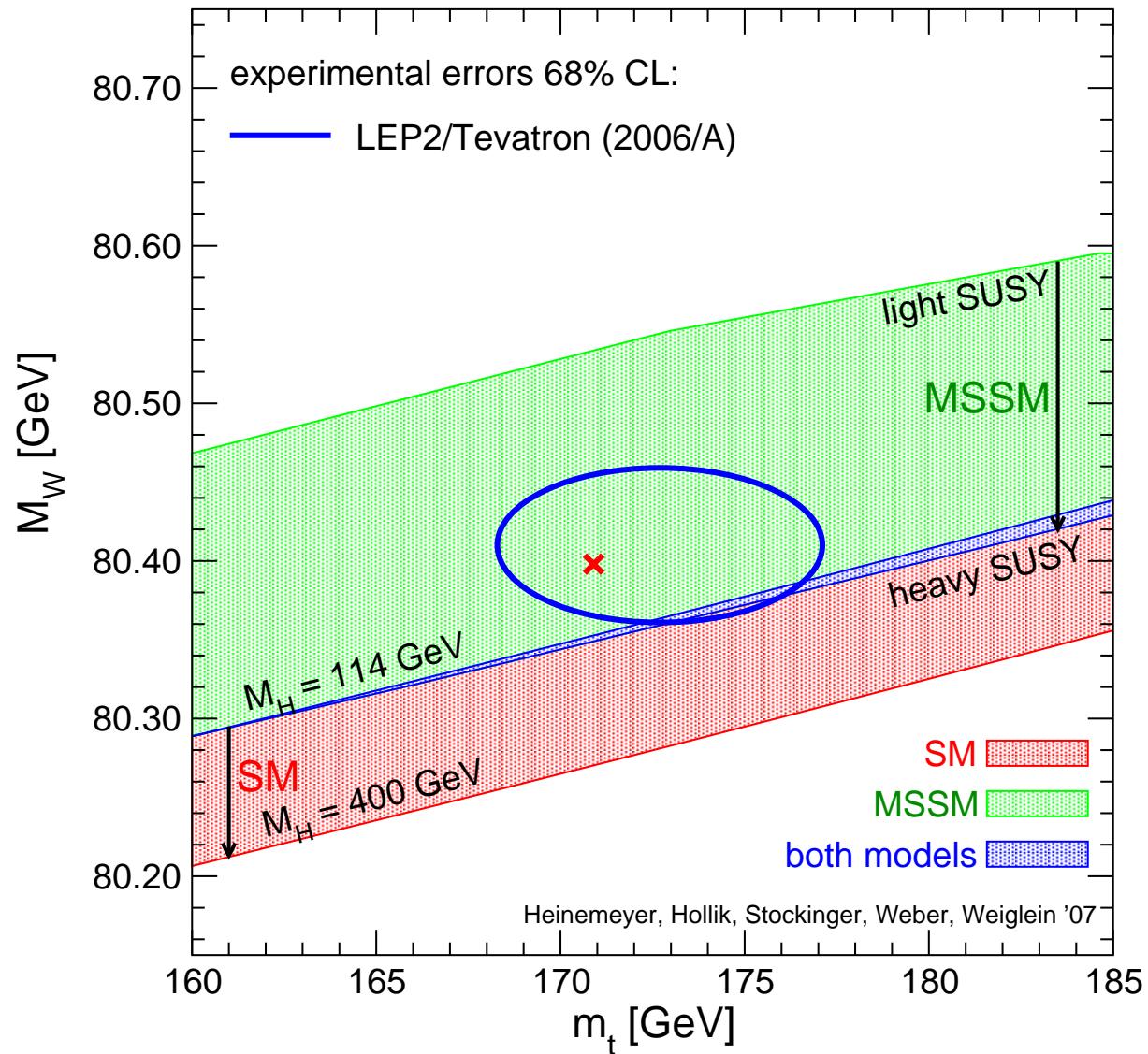
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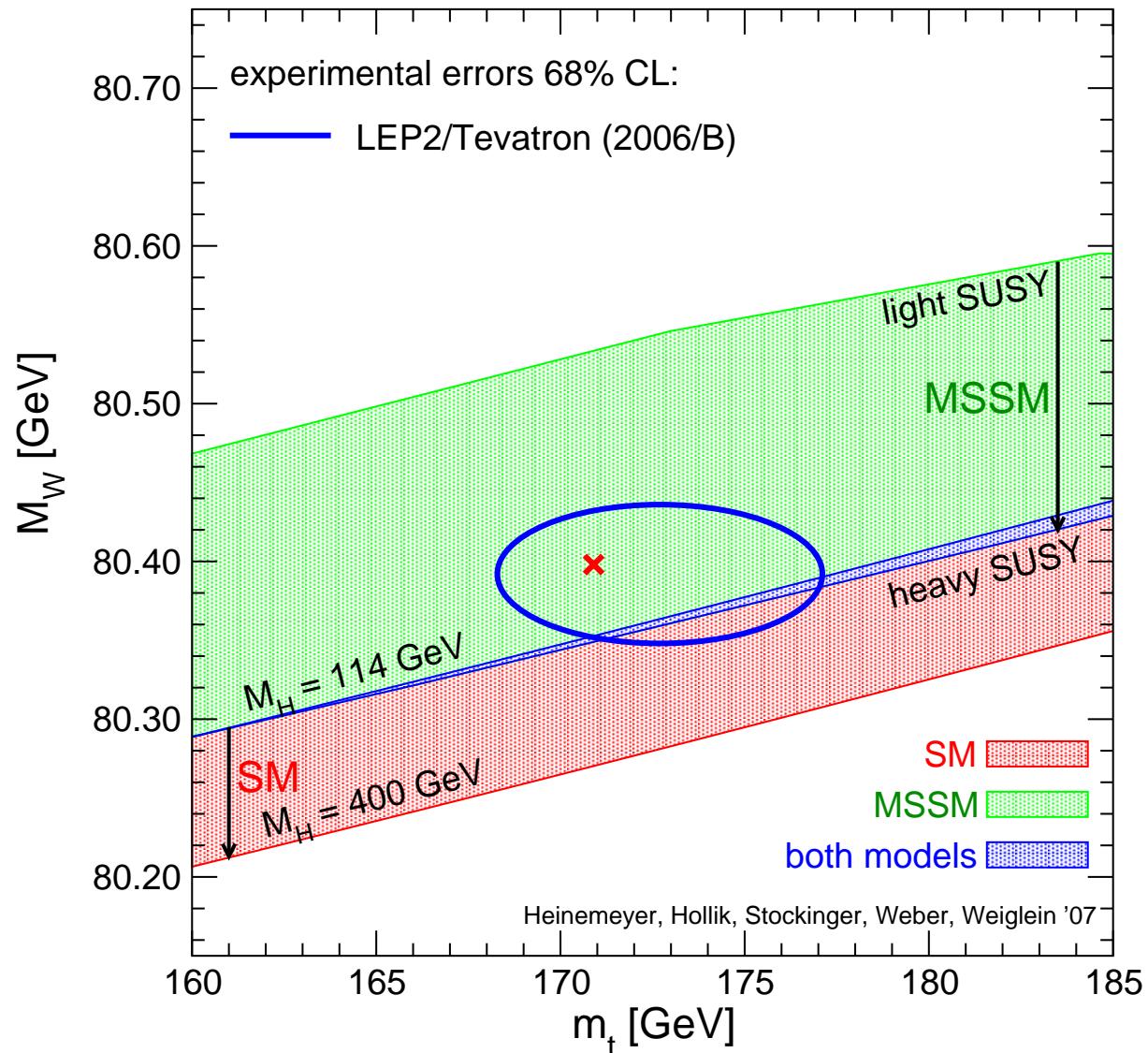
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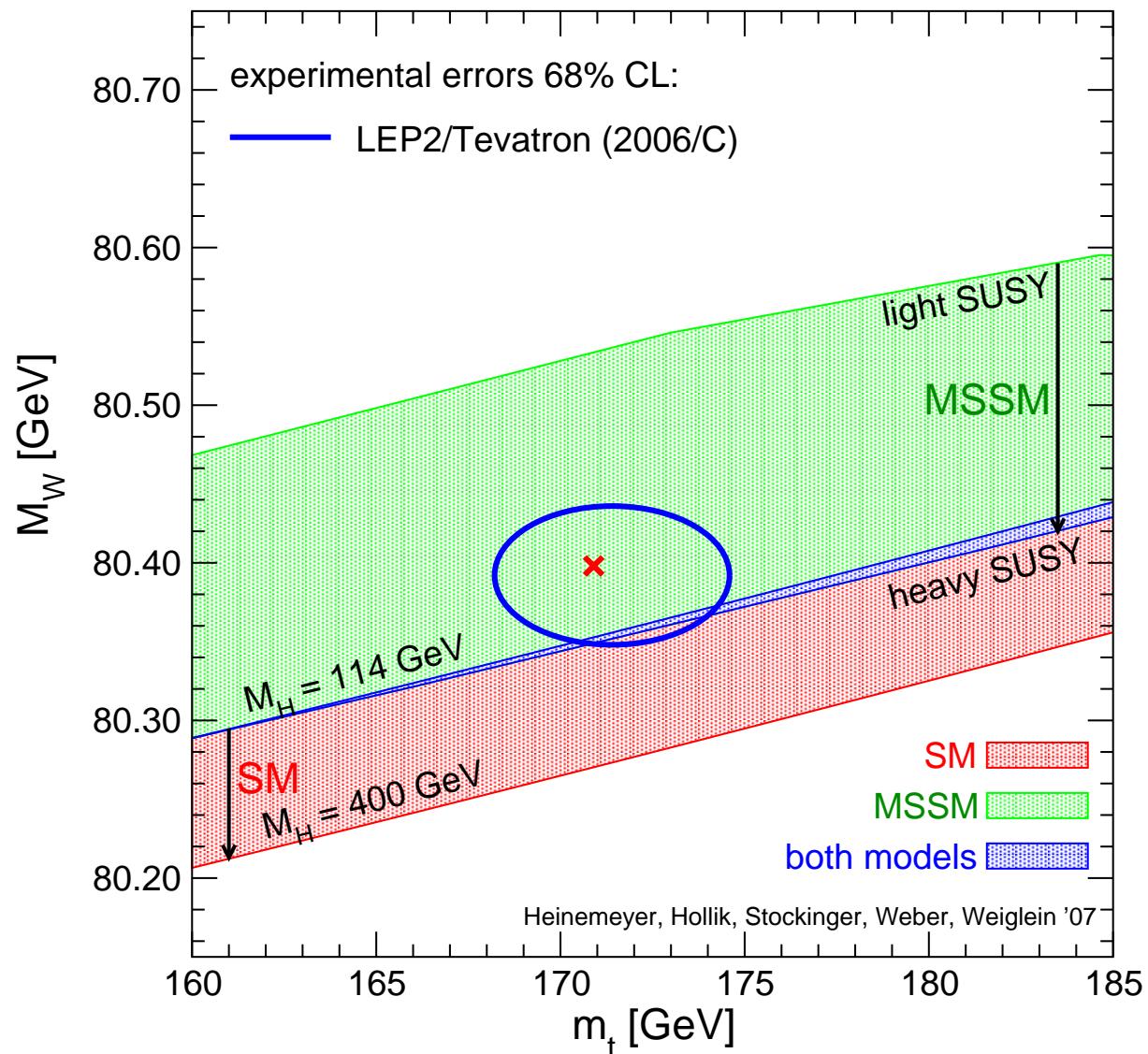
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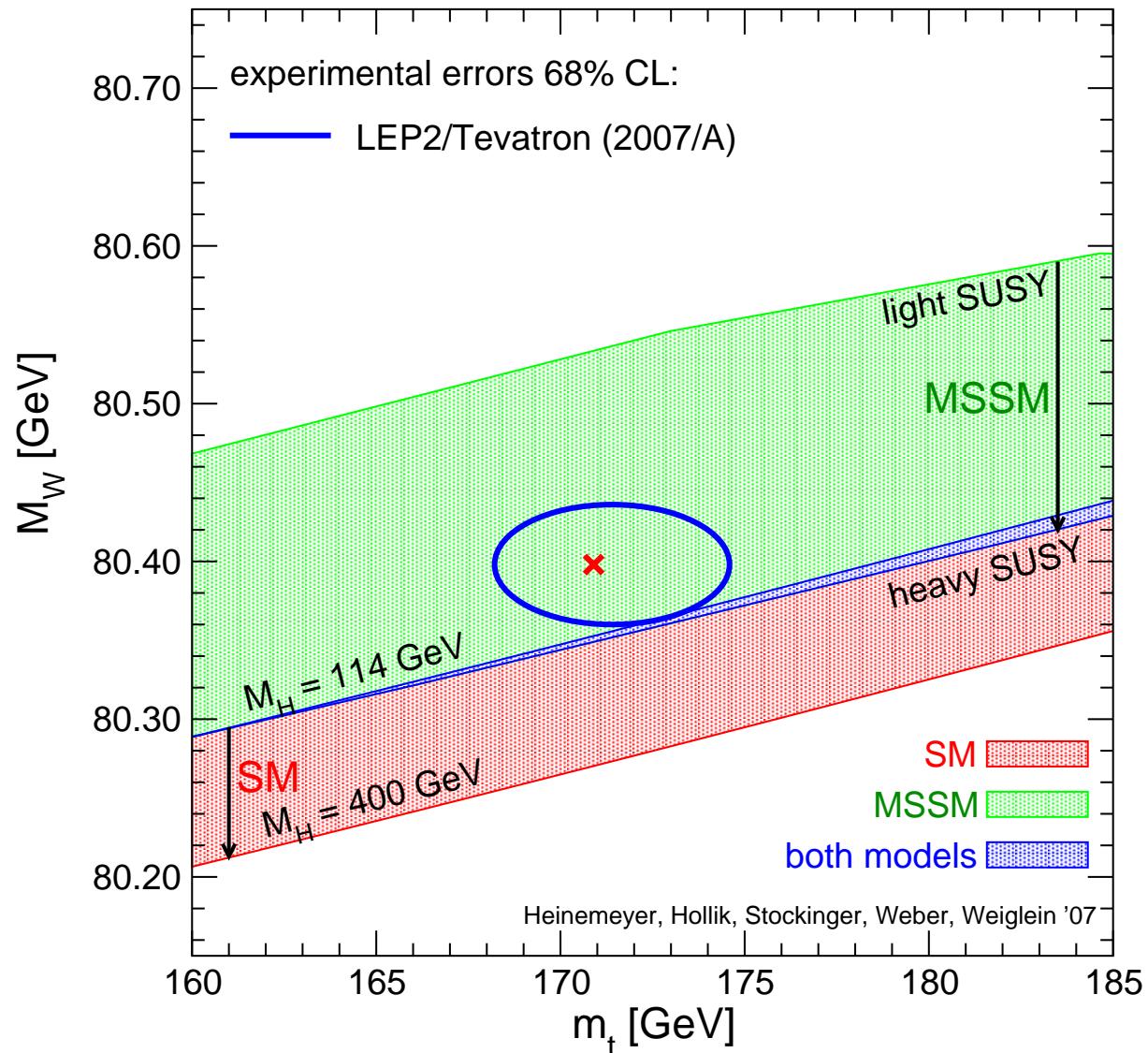
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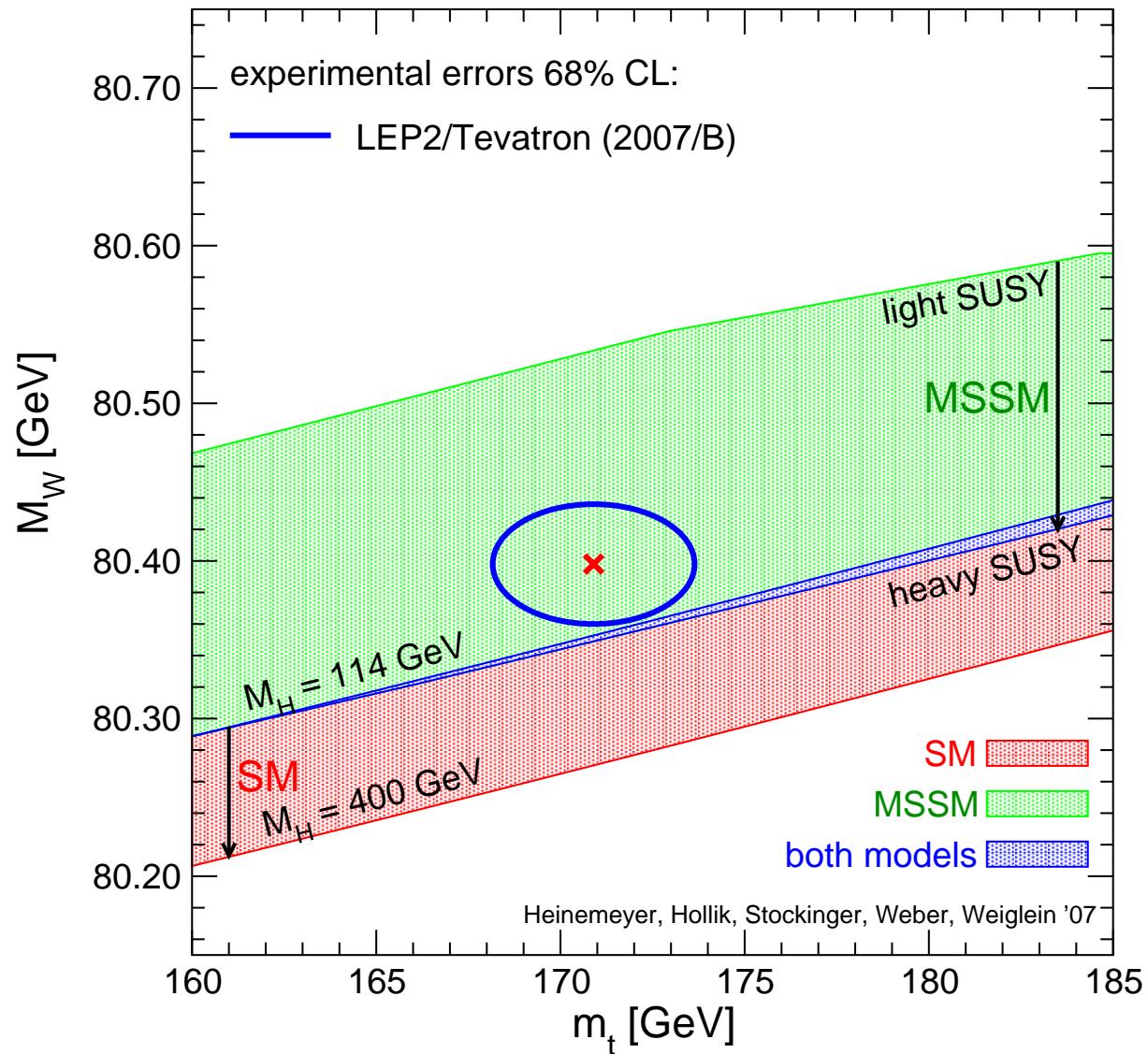
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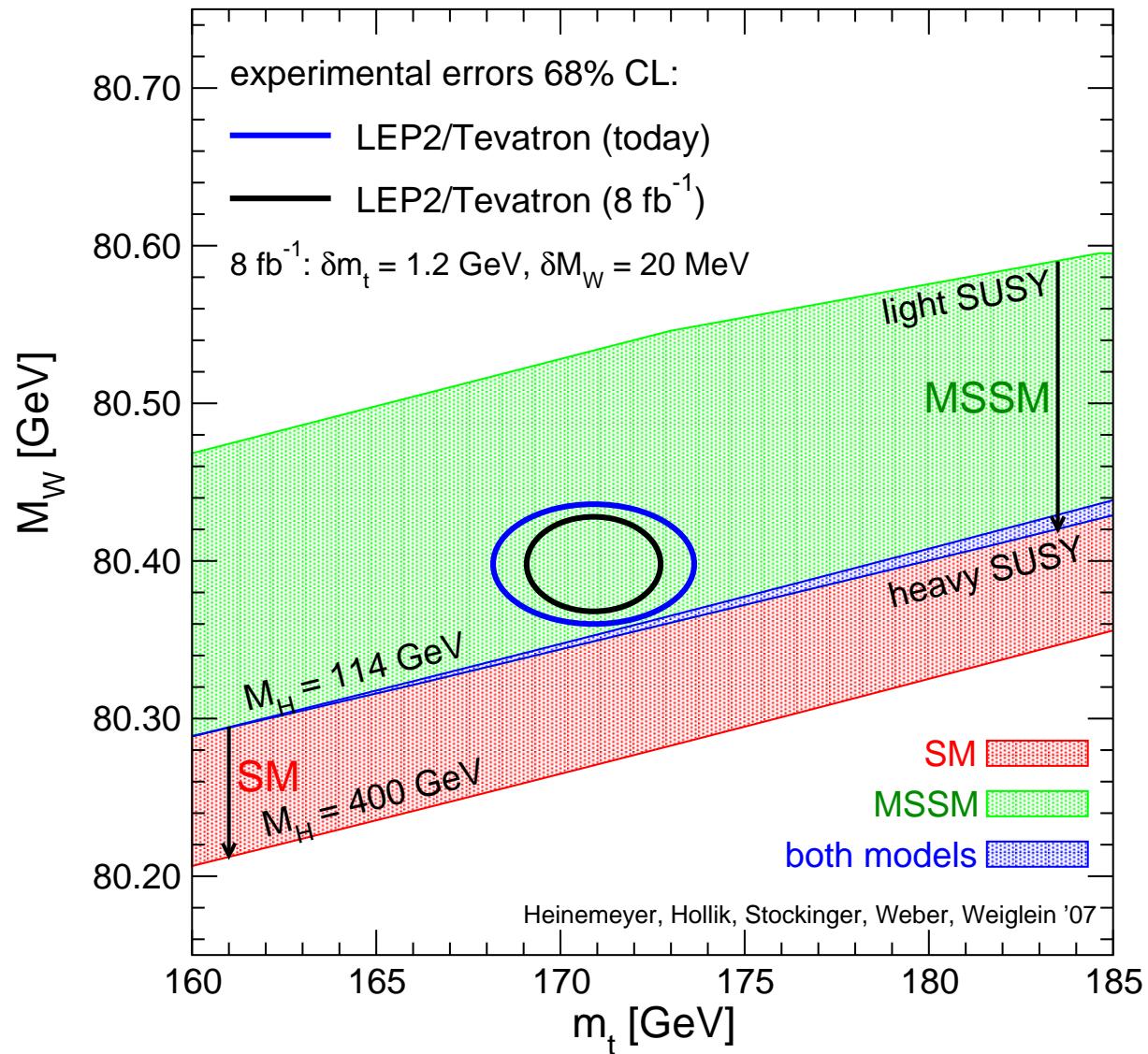
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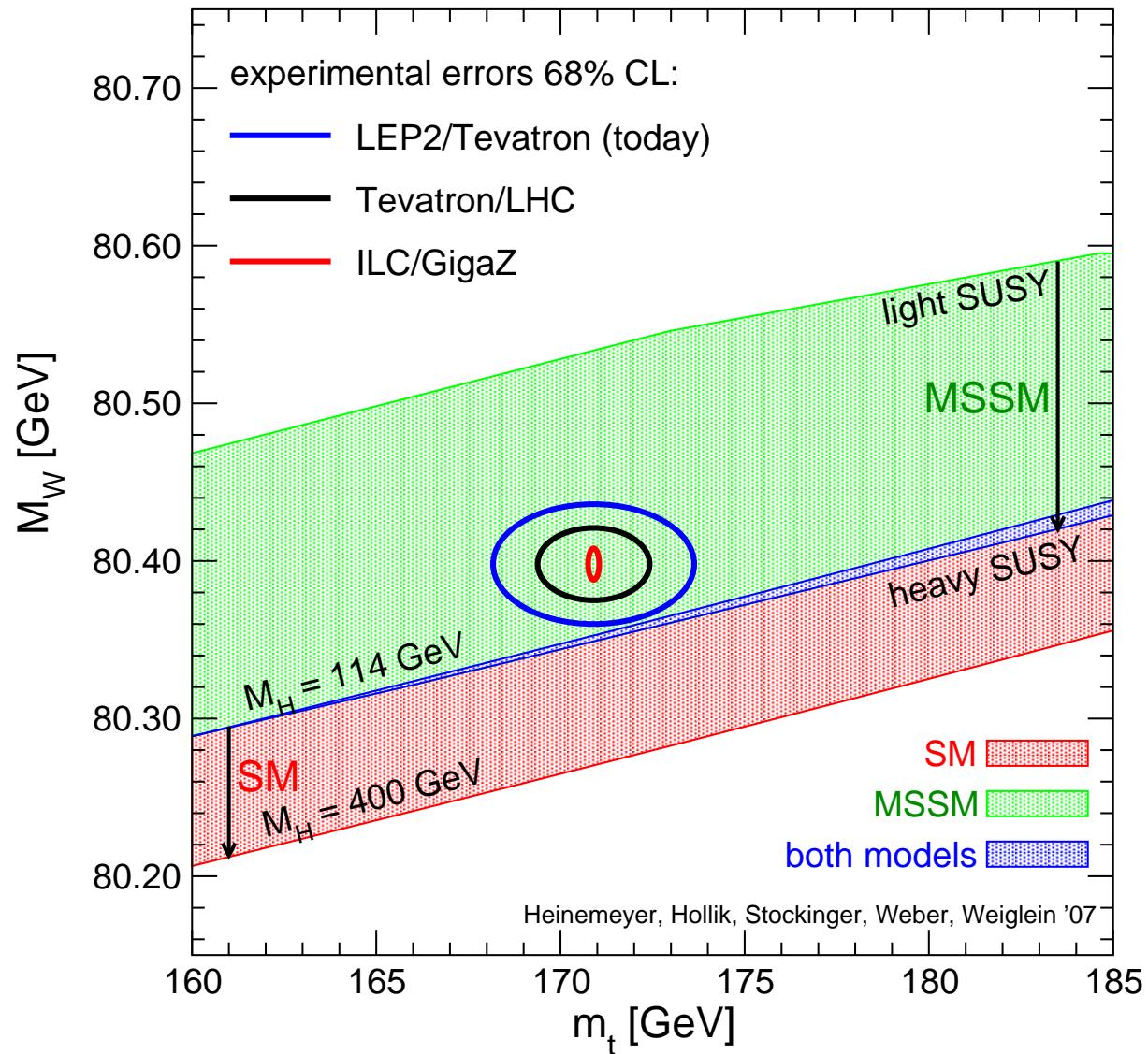
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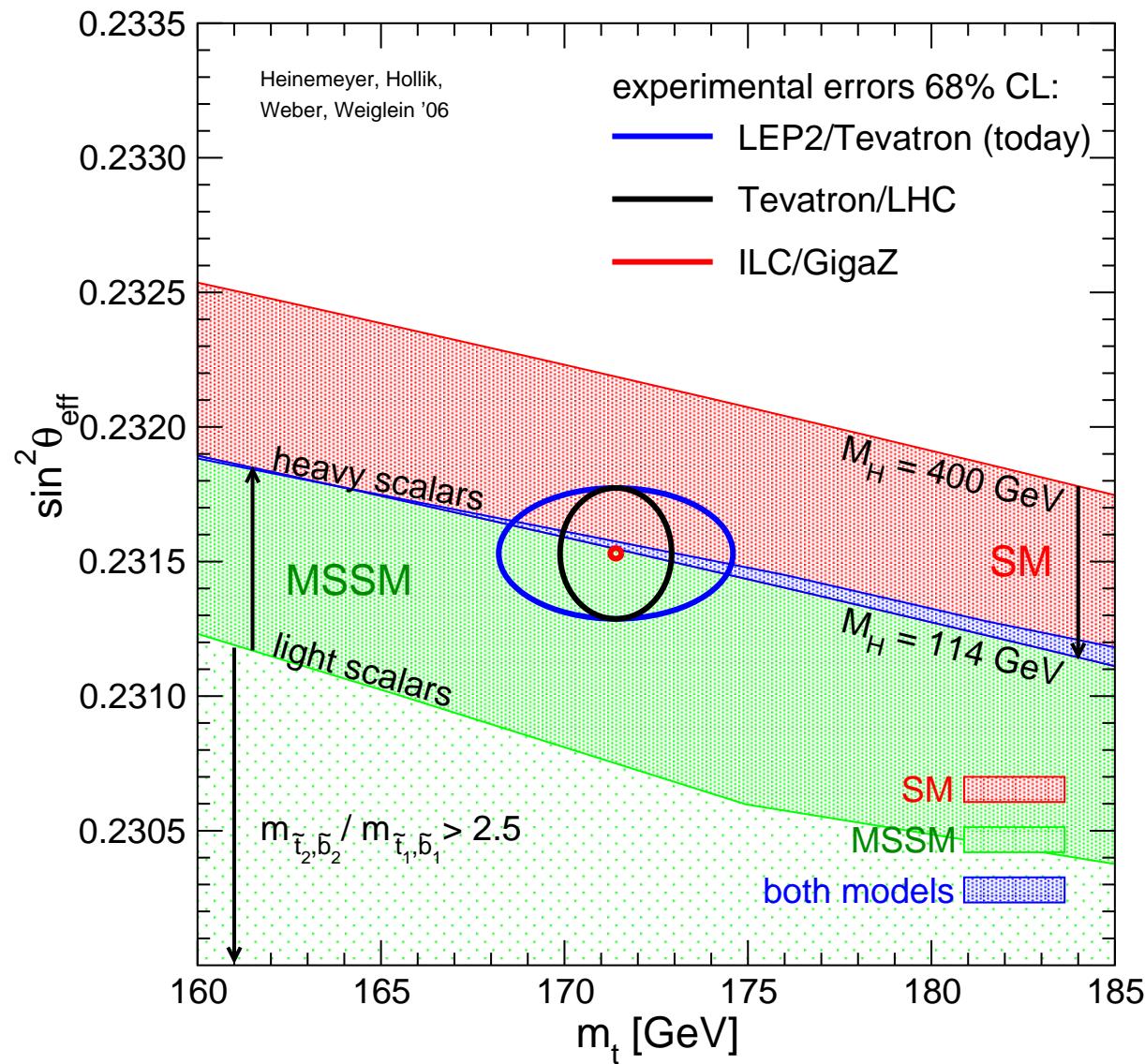
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Prediction for $\sin^2 \theta_{\text{eff}}$ in the SM and the MSSM :

[S.H., W. Hollik, A.M. Weber, G. Weiglein '07]



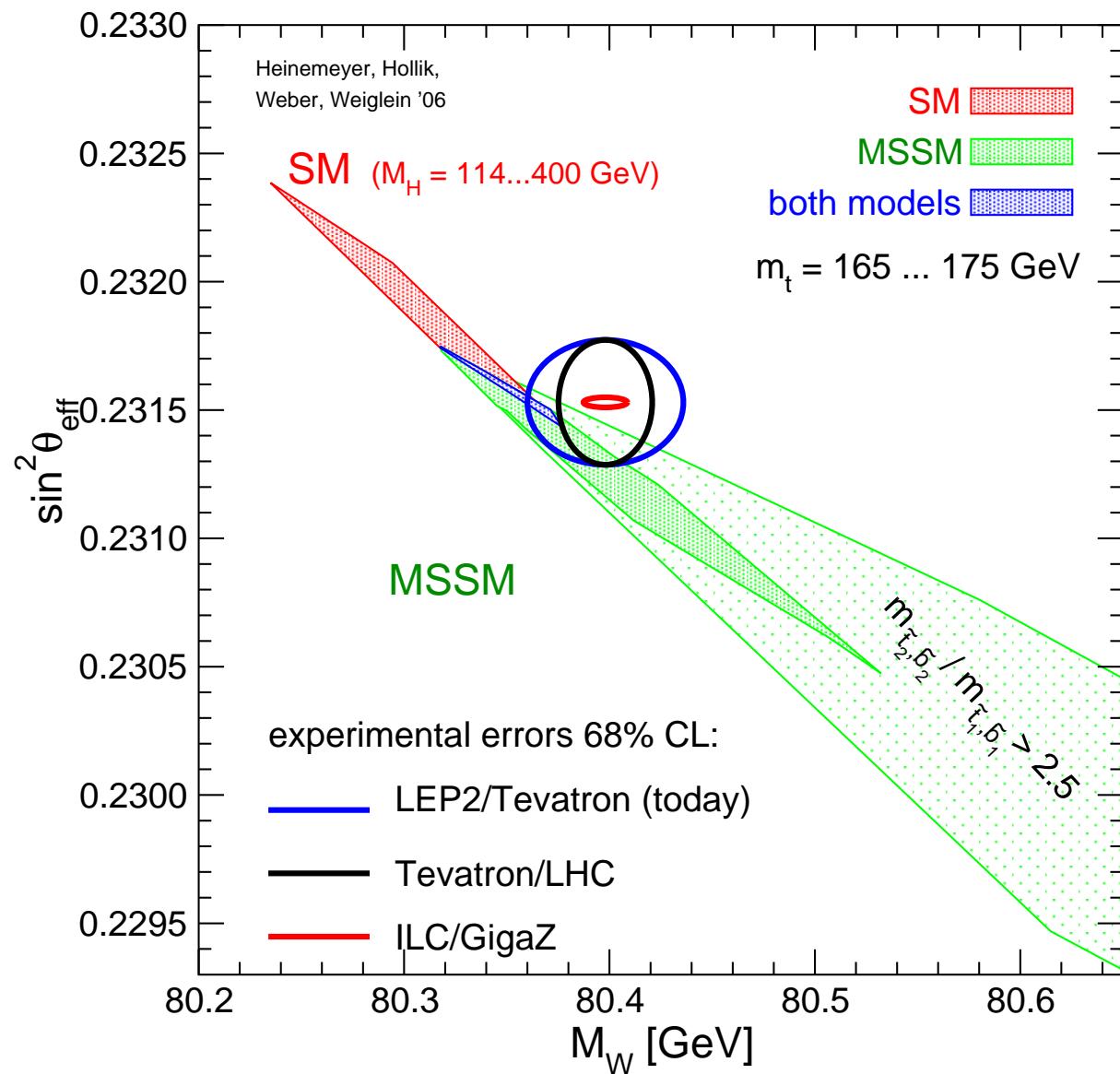
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Prediction for M_W and $\sin^2 \theta_{\text{eff}}$ in the **SM** and the **MSSM** :
 [S.H., W. Hollik, A.M. Weber, G. Weiglein '07]



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Experimental errors:

	today	Tev.	LHC	ILC	ILC with GigaZ
$\delta \sin^2 \theta_{\text{eff}} (\times 10^5)$	16	—	14–20	—	1.3
δM_W [MeV]	25	20	15	10	7

Relevant SM parametric errors: $\delta(\Delta\alpha_{\text{had}}) = 5 \times 10^{-5}$, $\delta M_Z = 2.1$ MeV

	$\delta m_t = 2$	$\delta m_t = 1$	$\delta m_t = 0.1$	$\delta(\Delta\alpha_{\text{had}})$	δM_Z
$\delta \sin^2 \theta_{\text{eff}} [10^{-5}]$	6	3	0.3	1.8	1.4
ΔM_W [MeV]	12	6	1	1	2.5

To keep the **parametric error induced by m_t** at/below the level of other uncertainties:

- ⇒ $\delta m_t \lesssim 0.2$ GeV for M_W
- ⇒ $\delta m_t \lesssim 0.5$ GeV for $\sin^2 \theta_{\text{eff}}$

WARNING (I):

The top-quark mass is becoming more and more precise . . .

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What top-quark mass are we measuring?

$$p\bar{p} \rightarrow t\bar{t} \rightarrow bW^+ \bar{b}W^- \rightarrow X$$

→ kinematic reconstruction

⇒ kinematic mass, \sim pole mass ?

→ new concepts necessary . . . [A. Hoang et al. '07]

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WARNING (II):

Are LO Monte Carlos (as used for CDF/D0) sufficient?

Another EWPO in the MSSM: the lightest Higgs boson mass M_h

Contrary to the SM: M_h is not a free parameter

MSSM tree-level bound: $M_h < M_Z$, excluded by LEP Higgs searches

Large radiative corrections:

Dominant one-loop corrections:

$$\Delta M_h^2 \sim G_\mu m_t^4 \log \left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2} \right)$$

The MSSM Higgs sector is connected to all other sector via loop corrections (especially to the scalar top sector) f

Measurement of M_h , Higgs couplings \Rightarrow test of the theory

LHC: $\Delta M_h \approx 0.2$ GeV

ILC: $\Delta M_h \approx 0.05$ GeV

$\Rightarrow M_h$ will be (the best?) electroweak precision observable

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Interested in MSSM Higgs physics?
Try our code **FeynHiggs**
www.feynhiggs.de

II

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A simplified version of the MSSM: CMSSM (mSUGRA):

⇒ Scenario characterized by

$$m_0, m_{1/2}, A_0, \tan \beta, \text{sign } \mu$$

m_0 : universal scalar mass parameter

$m_{1/2}$: universal gaugino mass parameter

A_0 : universal trilinear coupling

$\tan \beta$: ratio of Higgs vacuum expectation values

$\text{sign}(\mu)$: sign of supersymmetric Higgs parameter

} at the GUT scale

⇒ particle spectra from renormalization group running to weak scale

Lightest SUSY particle (LSP) is the lightest neutralino

A simplified version of the MSSM: CMSSM (mSUGRA)

⇒ Scenario characteristics

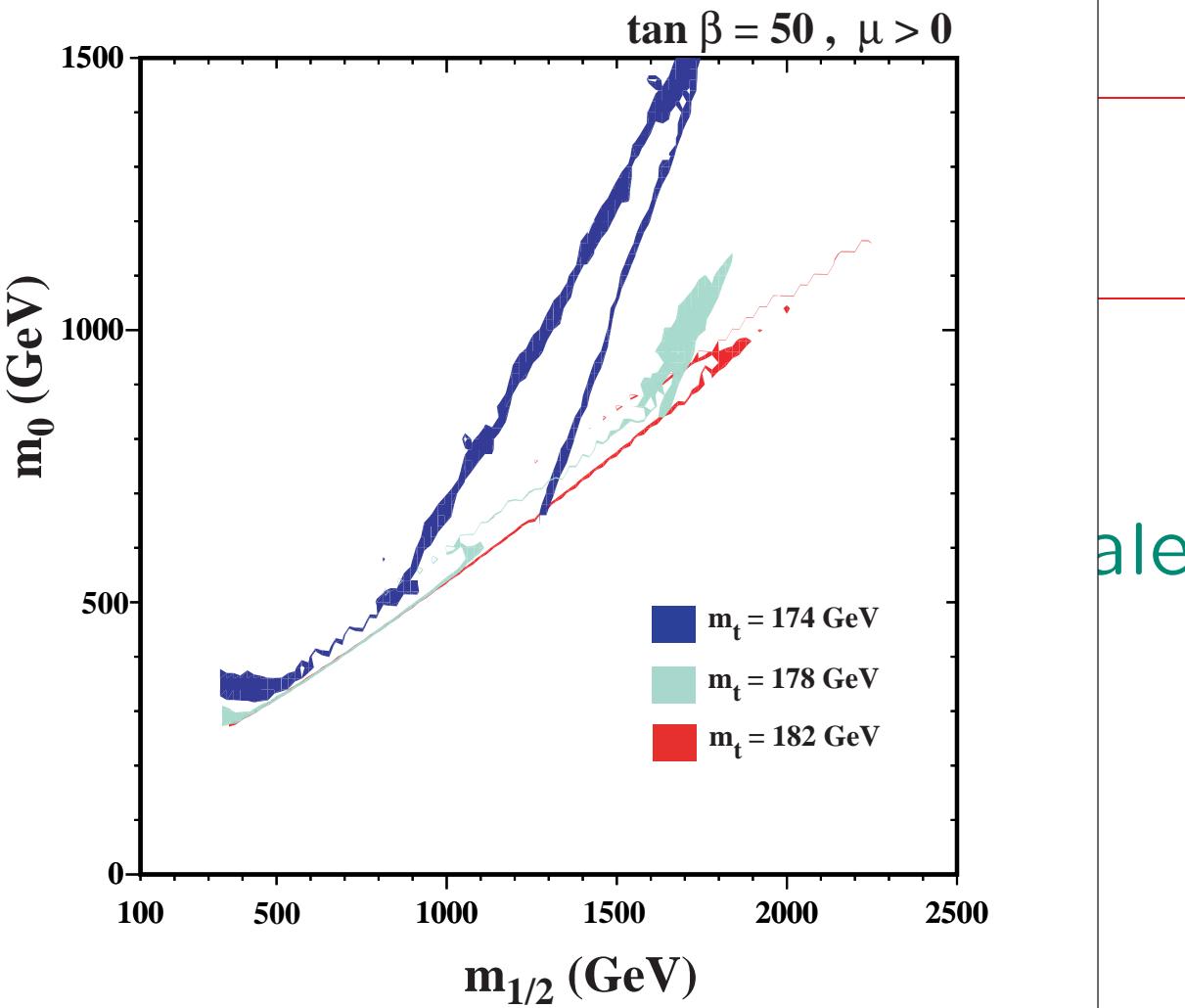
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$\tan \beta$: ratio of Higgs

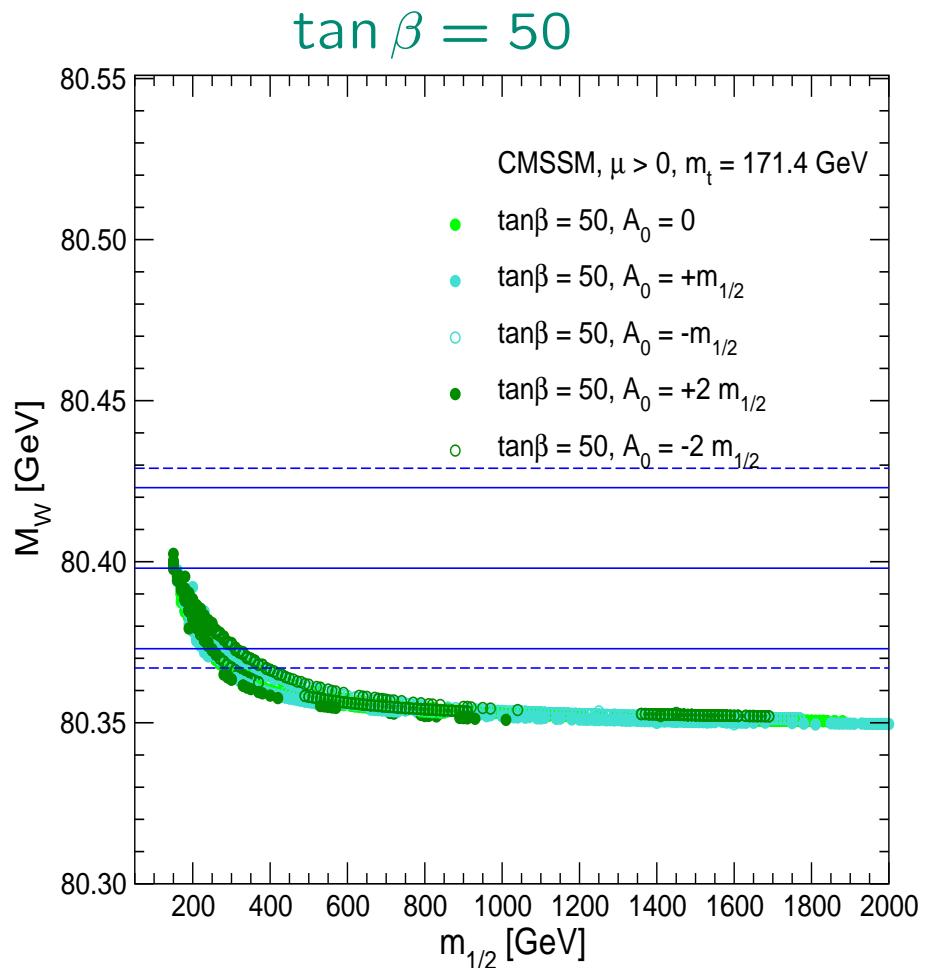
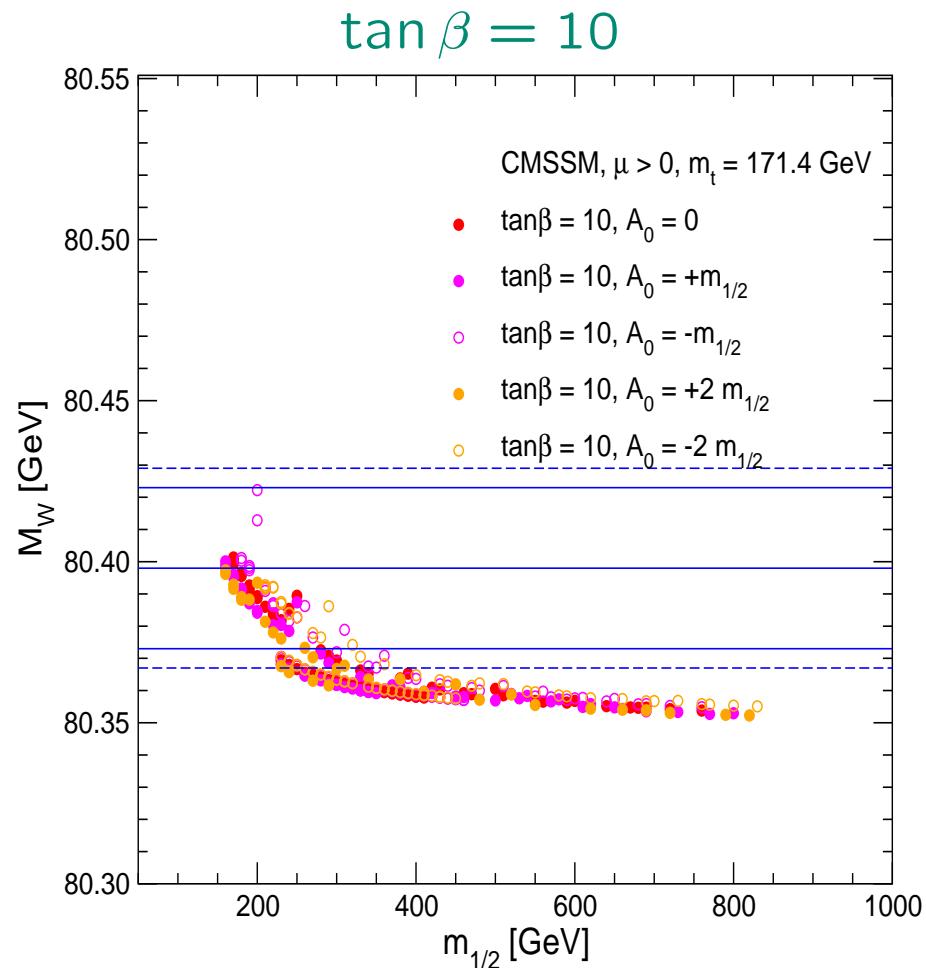
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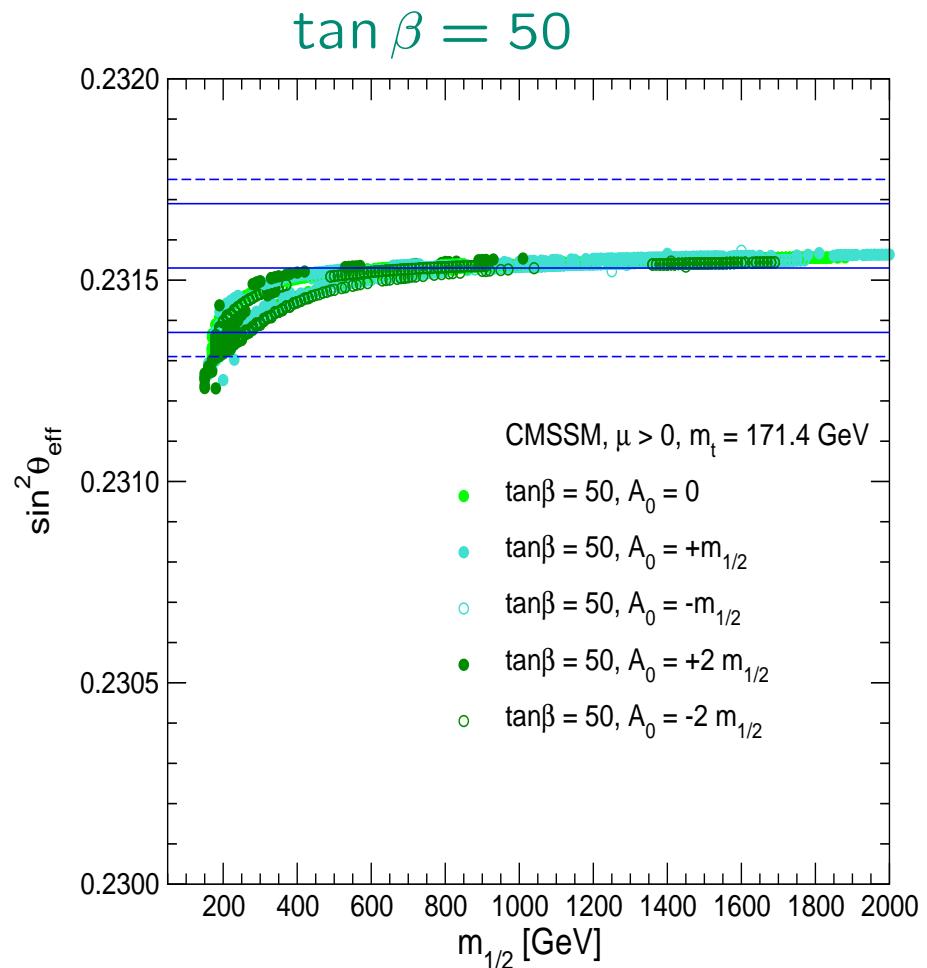
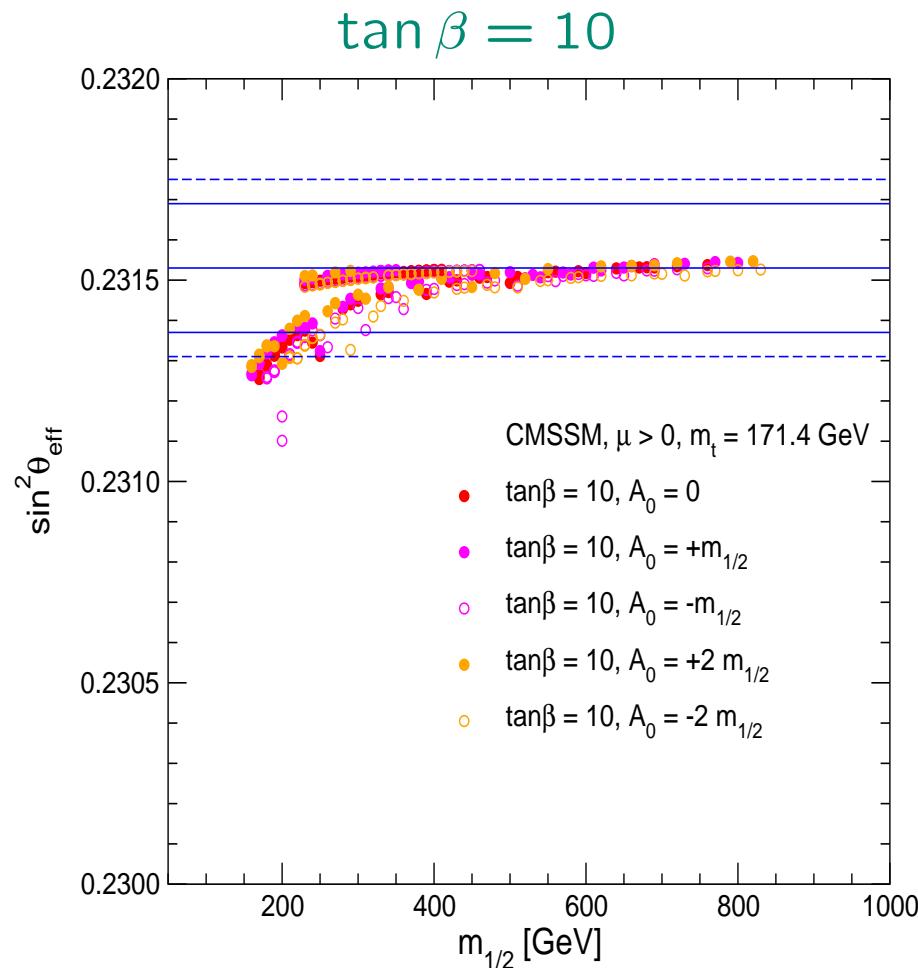
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Electroweak Precision Observables in the CMSSM: M_W



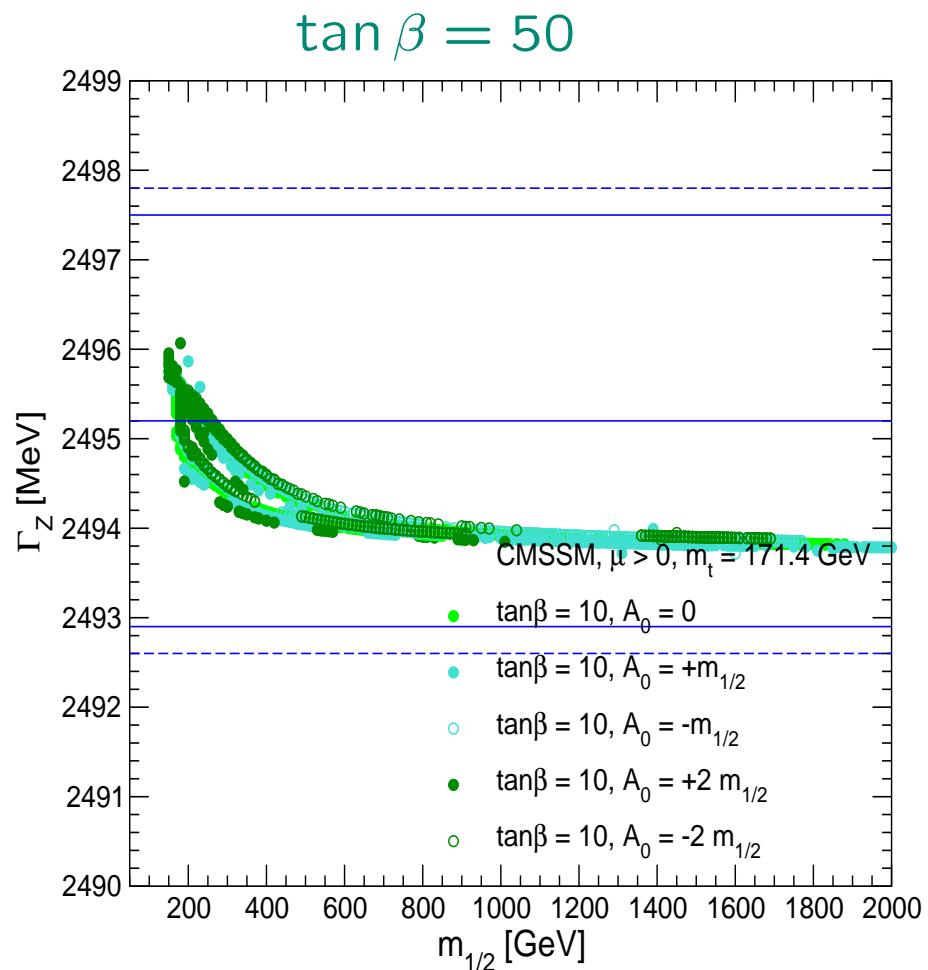
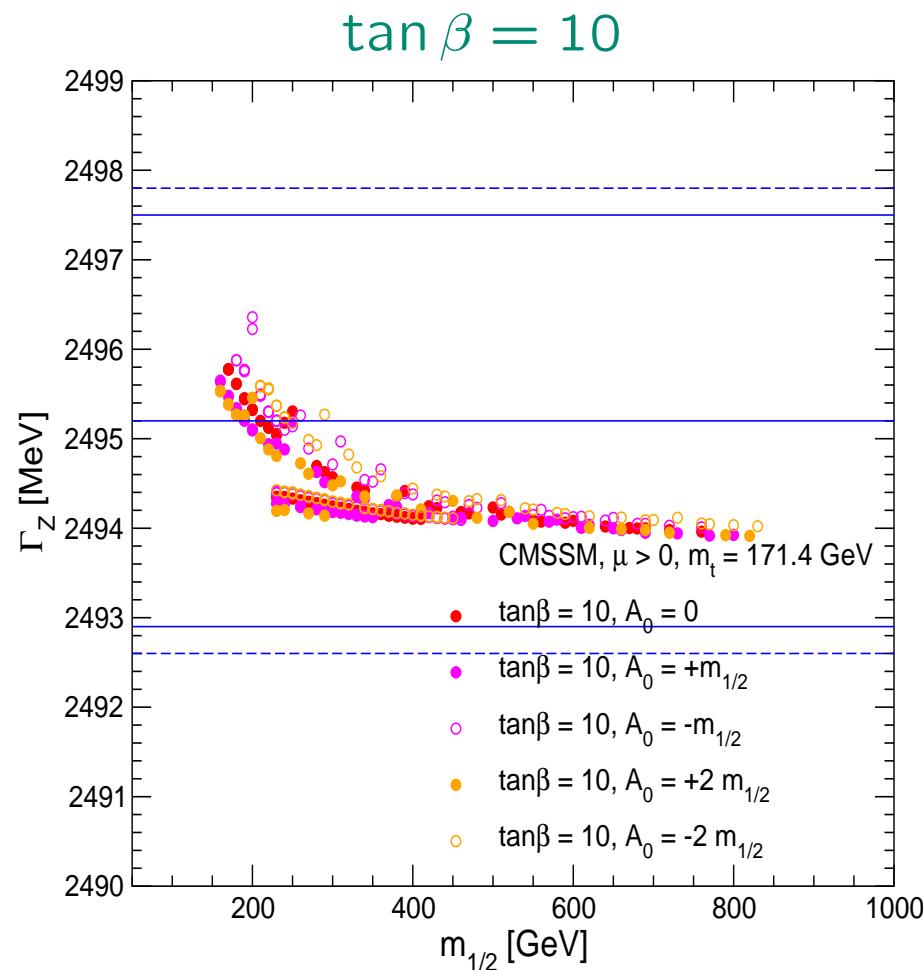
⇒ preference for light $m_{1/2}$

Electroweak Precision Observables in the CMSSM: $\sin^2 \theta_{\text{eff}}$



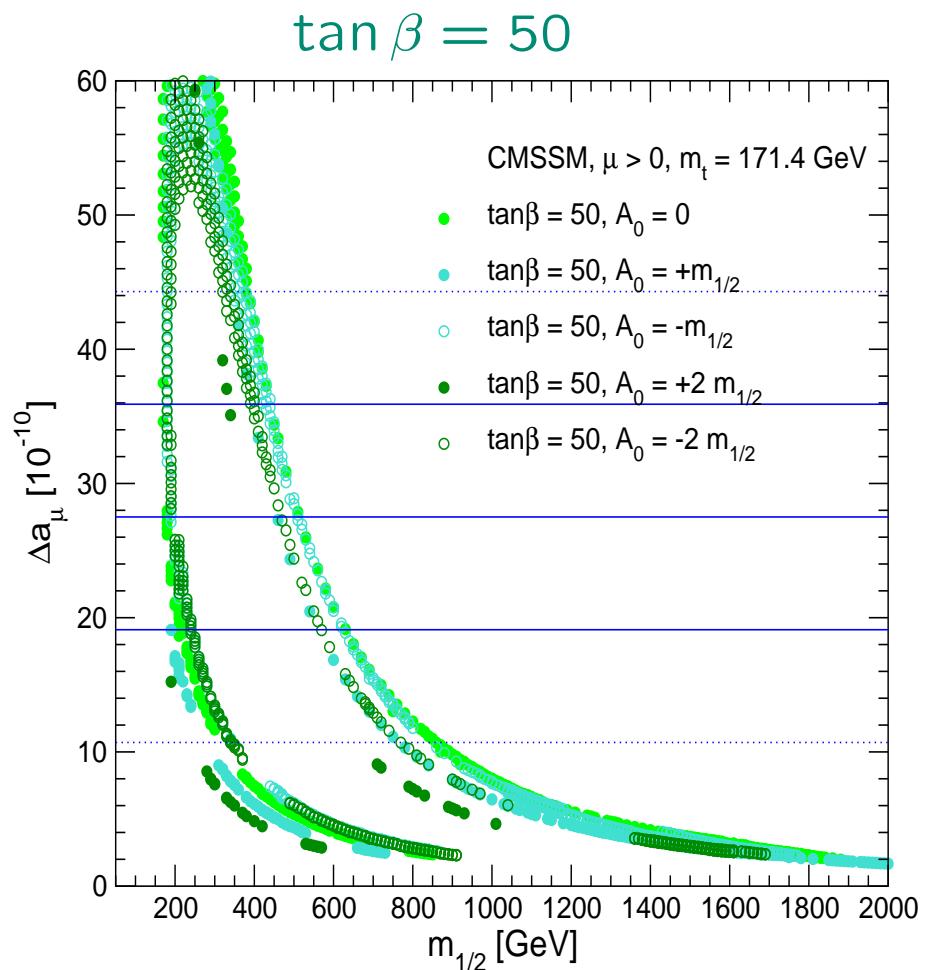
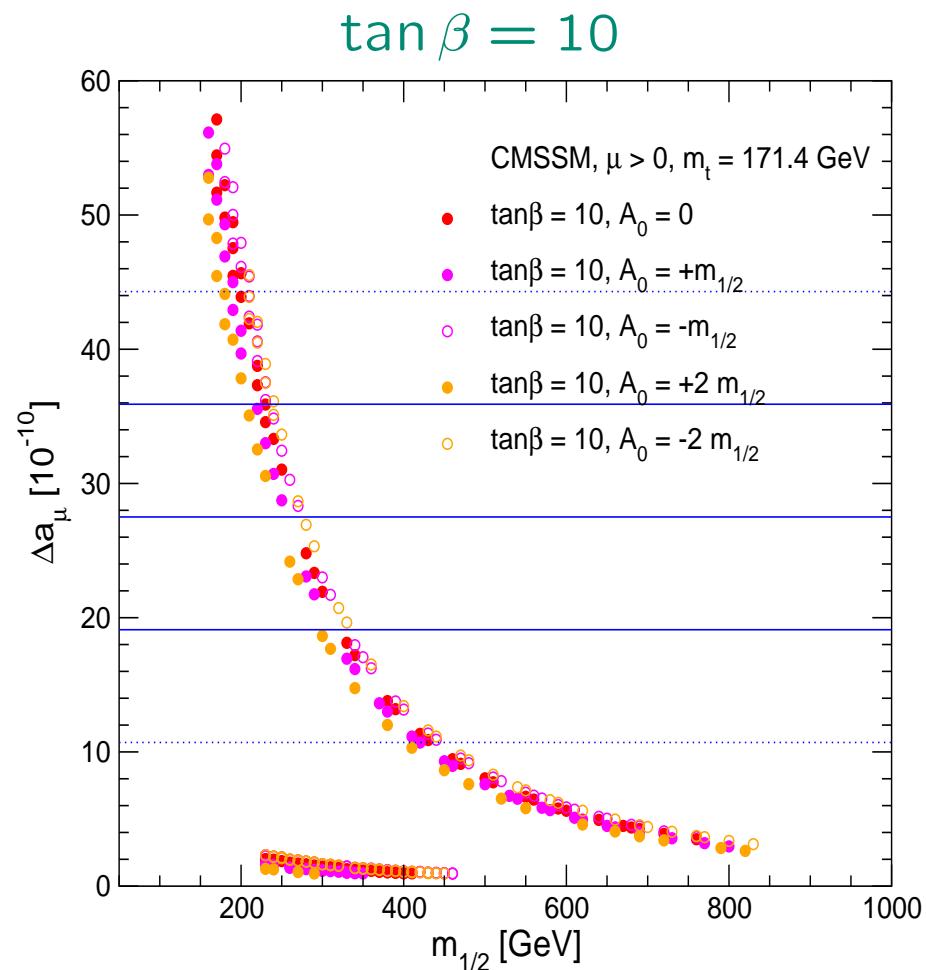
⇒ preference for larger $m_{1/2}$

Electroweak Precision Observables in the CMSSM: Γ_Z



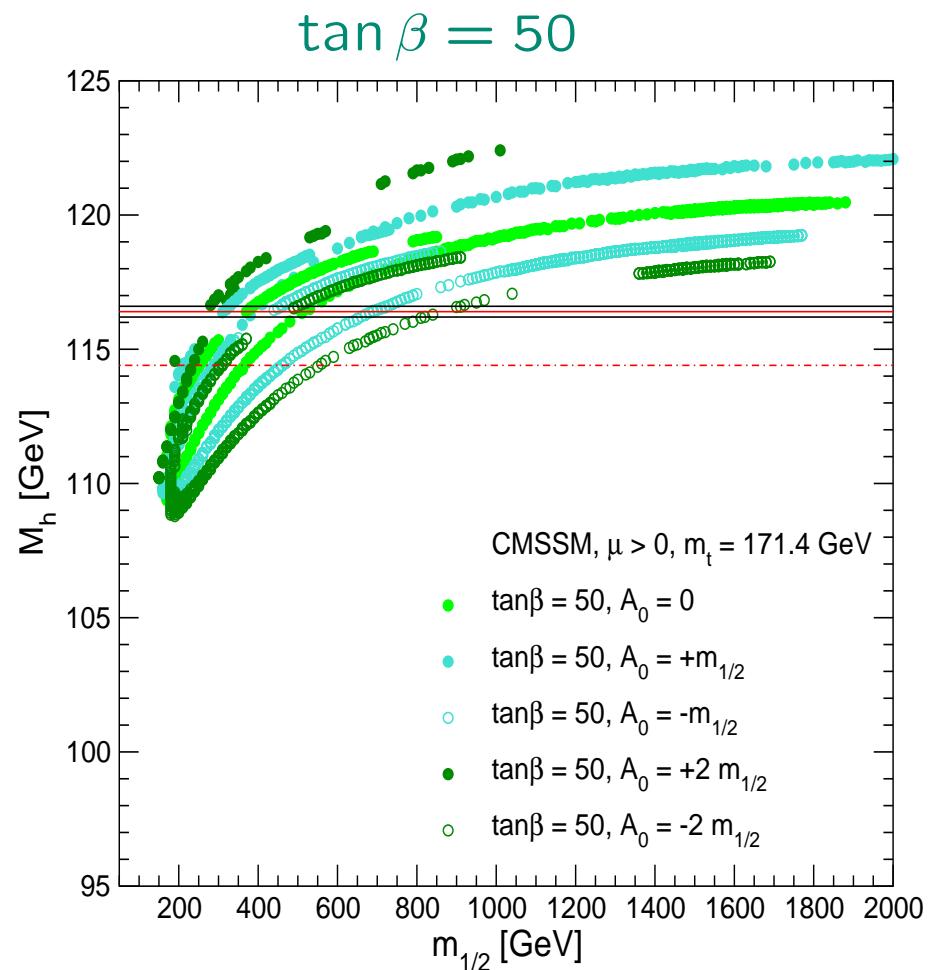
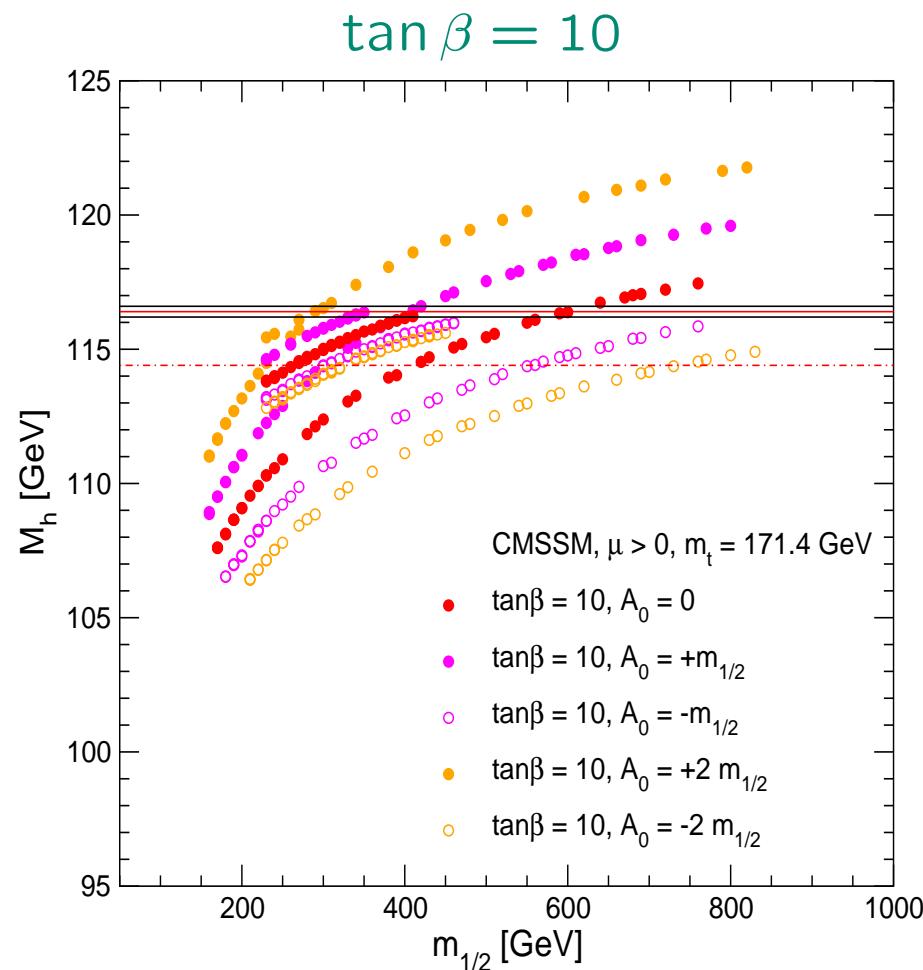
⇒ no preference for $m_{1/2}$

Electroweak Precision Observables in the CMSSM: $(g - 2)_\mu$



⇒ strong preference for light $m_{1/2}$

Electroweak Precision Observables in the CMSSM: M_h

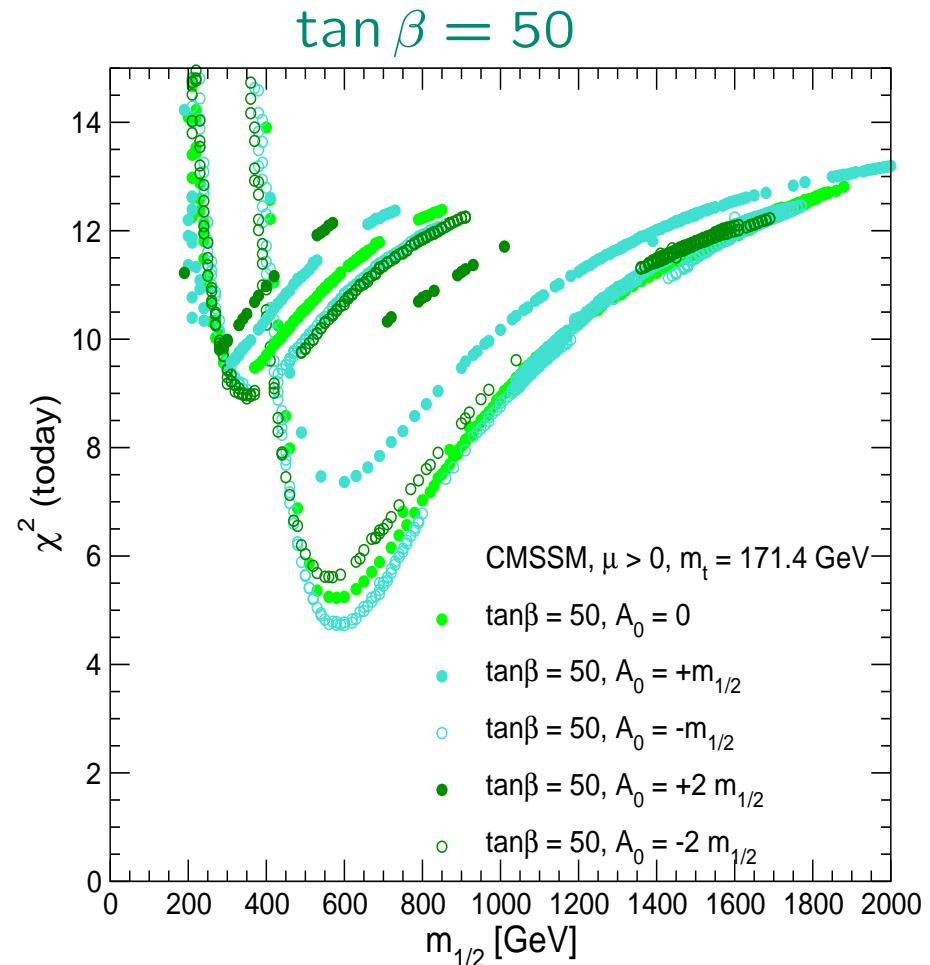
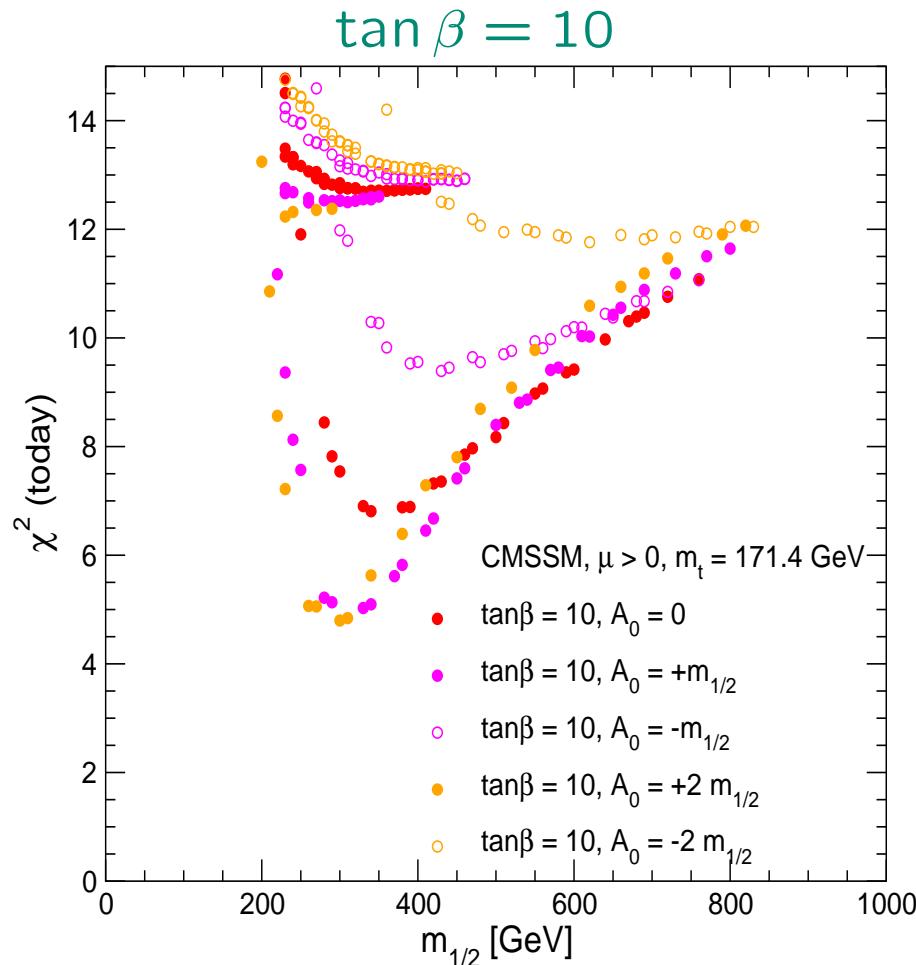


⇒ strong constraints on the CMSSM parameter space

Results: CMSSM: everything combined

(including BPO see talk by G. Weiglein)

[J. Ellis, S.H., K. Olive, A.M. Weber, G. Weiglein '07]



→ preference for somewhat smallish $m_{1/2}$ – but with a little tension

Global fit to all SM data:

[LEPEWWG '07]

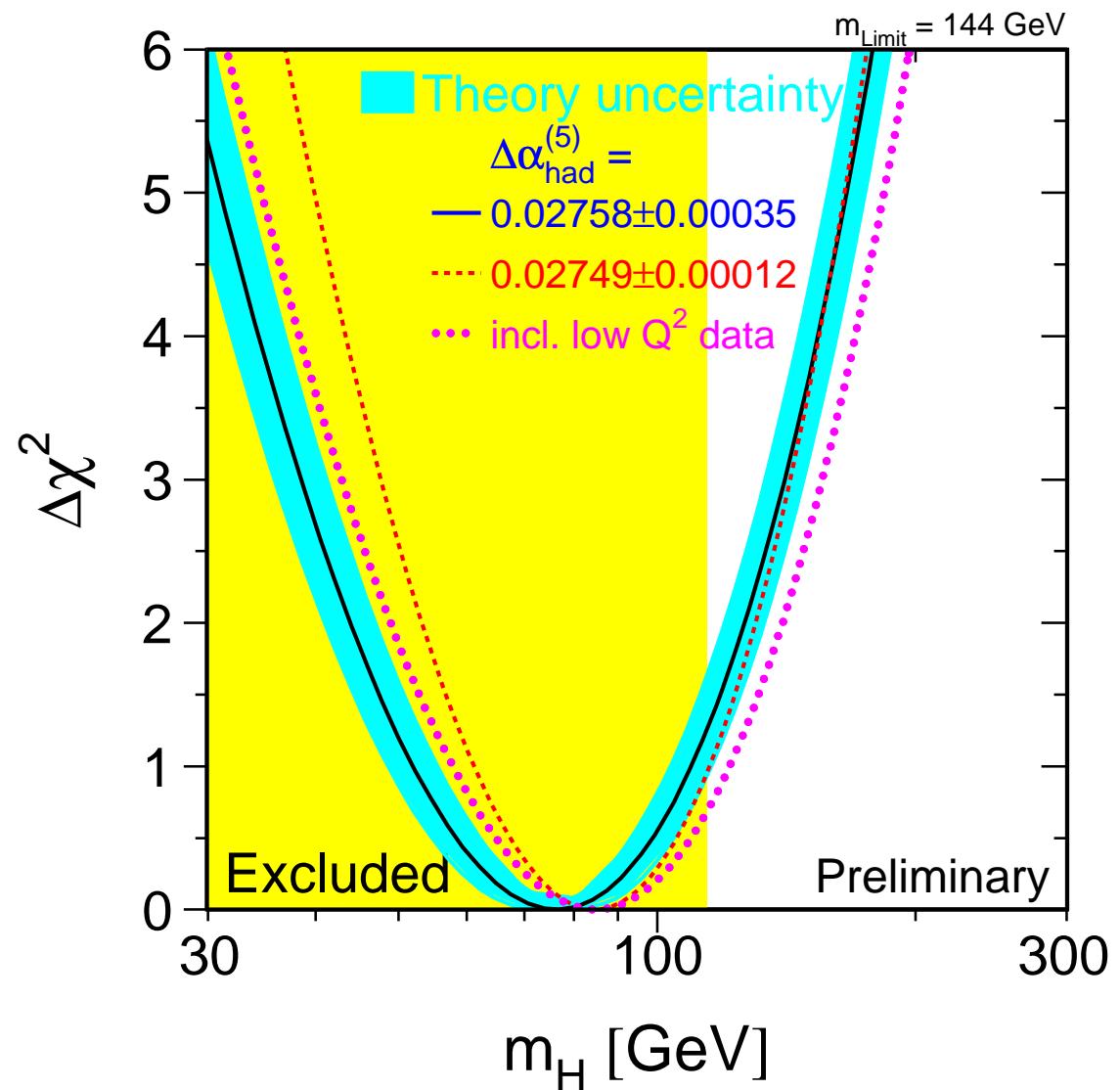
$$\Rightarrow M_H = 76^{+33}_{-24} \text{ GeV}$$

$M_H < 144 \text{ GeV}$, 95% C.L.

Assumption for the fit:

SM incl. Higgs boson

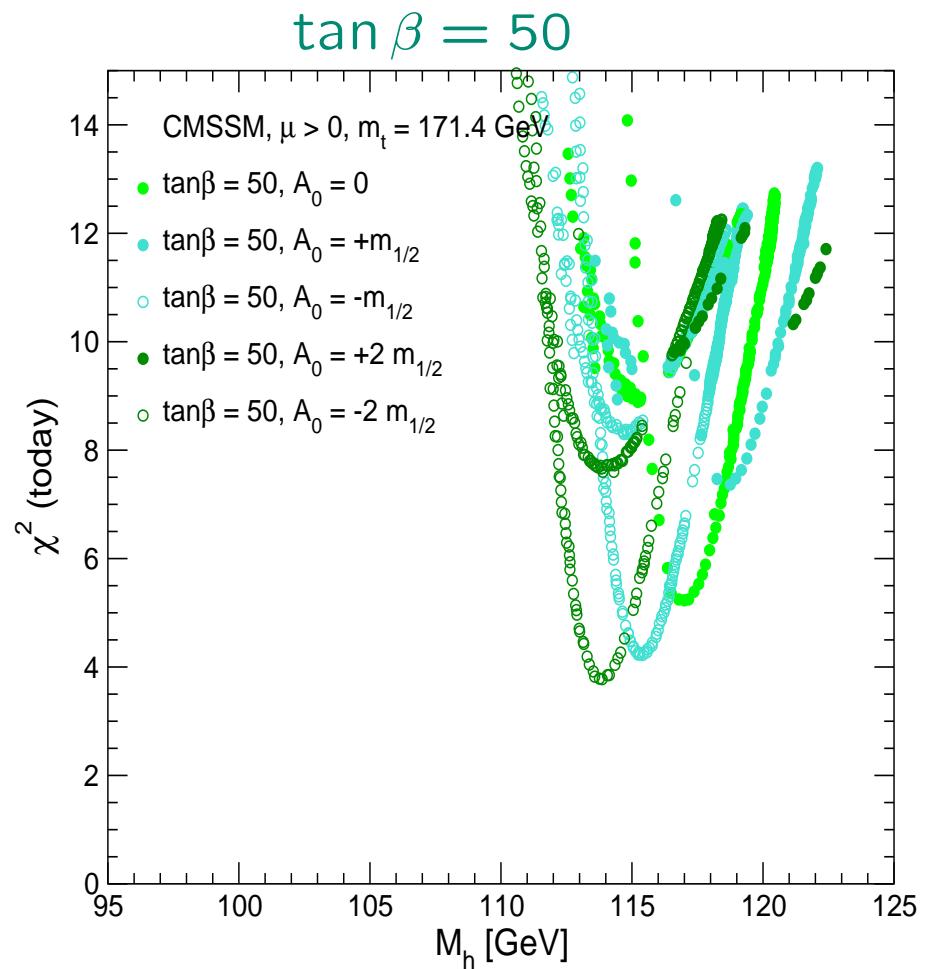
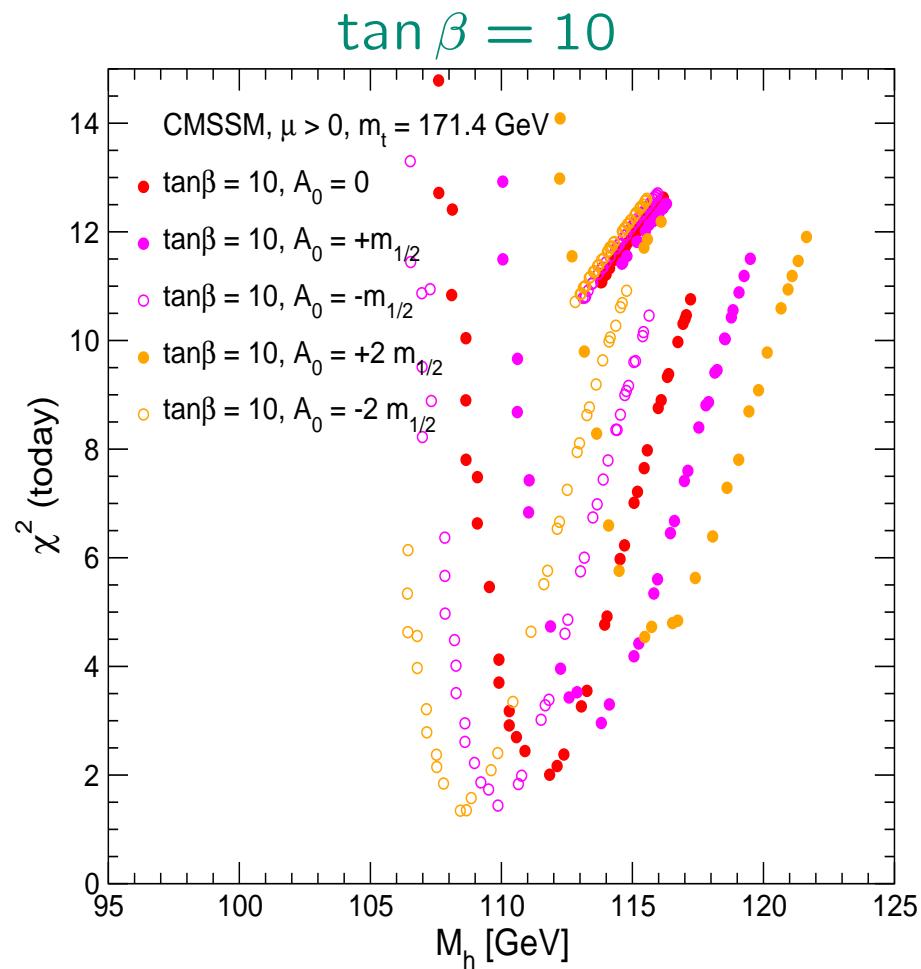
\Rightarrow no confirmation of
Higgs mechanism



\Rightarrow Higgs boson seems to be light – too light?

Results: CMSSM: “blue band” for M_h

[J. Ellis, S.H., K. Olive, A.M. Weber, G. Weiglein '07]



⇒ much “better” than in the SM

Final idea:

[Buchmüller, Cavanaugh, de Roeck, S.H., Isidori, Paradisi, Ronga, Weber, G. Weiglein '07]

- combine all electroweak precision data as in the SM
- combine B physics observables
- include SM parameters with their errors: m_t , ...
- scan over the full CMSSM parameter space

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⇒ preferred M_h values

⇒ LHC/ILC reach

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Most important:

Produce better graphics! :-)

Pull distributions:

[Buchmüller, Cavanaugh, de Roeck, S.H., Isidori, Paradisi, Ronga, Weber, G. Weiglein '07]

CMSSM

Variable	Measurement	Fit	$ O_{\text{meas}} - O_{\text{fit}} /\sigma_{\text{meas}}$
$\Delta\alpha_{\text{had}}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02774	0
m_Z [GeV]	91.1875 ± 0.0021	91.1873	0
Γ_Z [GeV]	2.4952 ± 0.0023	2.4952	0
σ_{had}^0 [nb]	41.540 ± 0.037	41.486	1
R_l	20.767 ± 0.025	20.744	1
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01641	1
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1479	0
R_b	0.21629 ± 0.00066	0.21613	0
R_c	0.1721 ± 0.0030	0.1722	0
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037	2
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0741	1
A_b	0.923 ± 0.020	0.935	0
A_c	0.670 ± 0.027	0.668	0
$A_l(\text{SLD})$	0.1513 ± 0.0021	0.1479	1
$\sin^2\theta_{\text{eff}}^{\text{lept}}(Q_{fb})$	0.2324 ± 0.0012	0.2314	1
m_W [GeV]	80.398 ± 0.025	80.382	1
m_t [GeV]	170.9 ± 1.8	170.8	0
$R(b \rightarrow s\gamma)$	1.13 ± 0.12	1.12	0
$B_s \rightarrow \mu\mu$ [$\times 10^{-8}$]	< 8.00	0.33	N/A (upper limit)
Δa_μ [$\times 10^{-9}$]	2.95 ± 0.87	2.95	
Ωh^2	0.113 ± 0.009	0.113	

SM

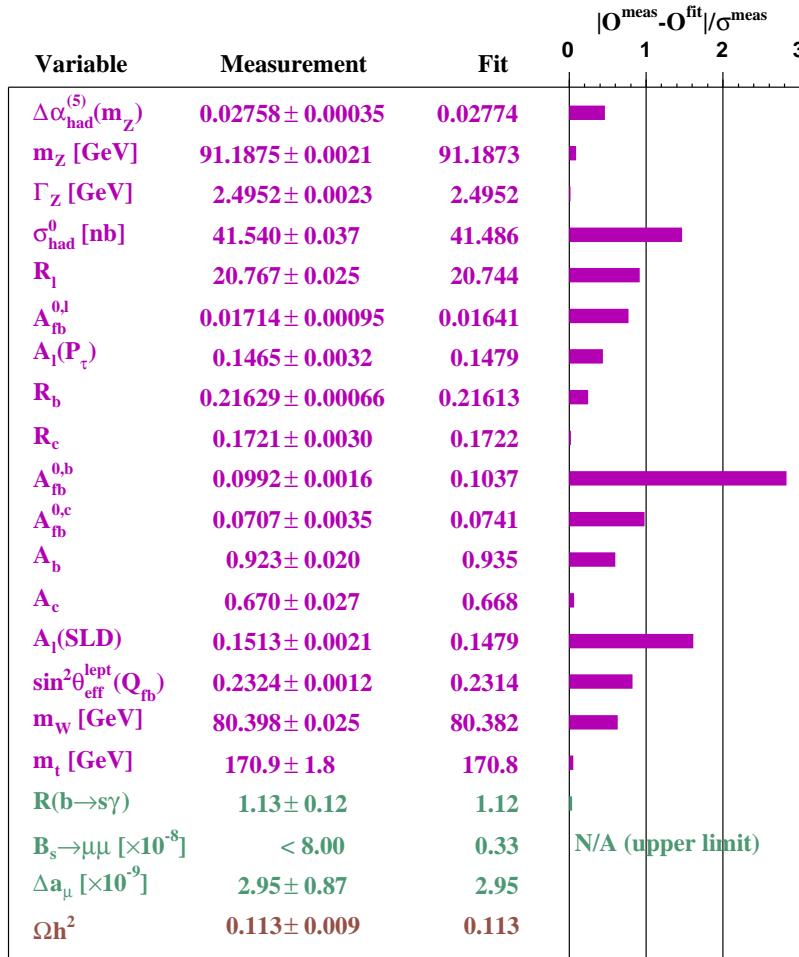
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$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481	0
R_b	0.21629 ± 0.00066	0.21586	1
R_c	0.1721 ± 0.0030	0.1722	0
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038	2
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742	1
A_b	0.923 ± 0.020	0.935	0
A_c	0.670 ± 0.027	0.668	0
$A_l(\text{SLD})$	0.1513 ± 0.0021	0.1481	1
$\sin^2\theta_{\text{eff}}^{\text{lept}}(Q_{fb})$	0.2324 ± 0.0012	0.2314	1
m_W [GeV]	80.398 ± 0.025	80.374	1
m_t [GeV]	170.9 ± 1.8	171.3	0
Γ_W [GeV]	2.140 ± 0.060	2.091	1

⇒ note the new observables: $\text{BR}(b \rightarrow s\gamma)$, $(g-2)_\mu$, CDM

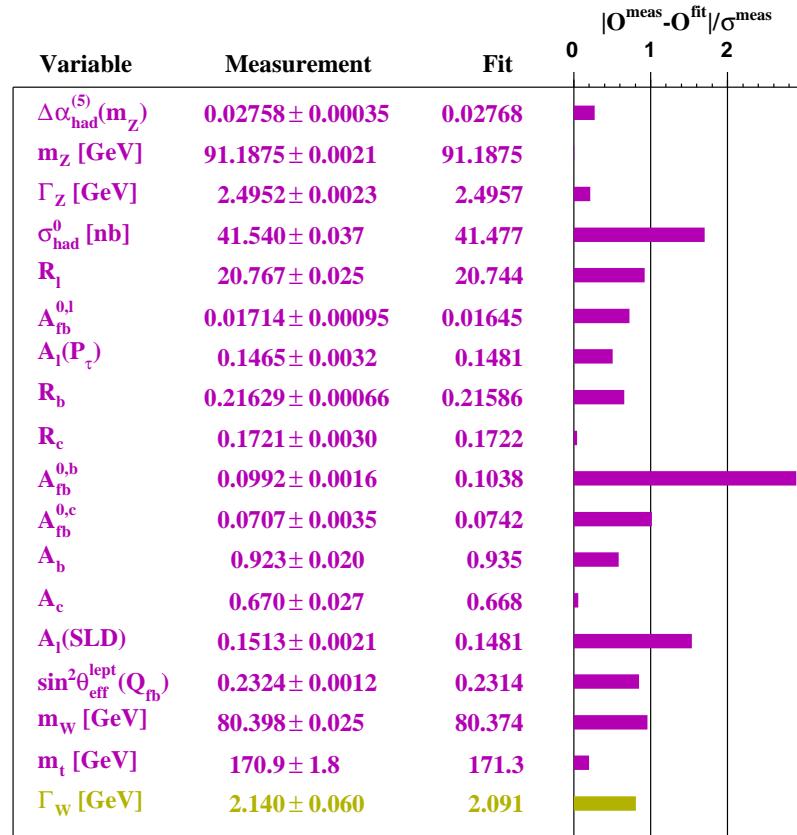
Pull distributions:

[Buchmüller, Cavanaugh, de Roeck, S.H., Isidori, Paradisi, Ronga, Weber, G. Weiglein '07]

CMSSM



SM

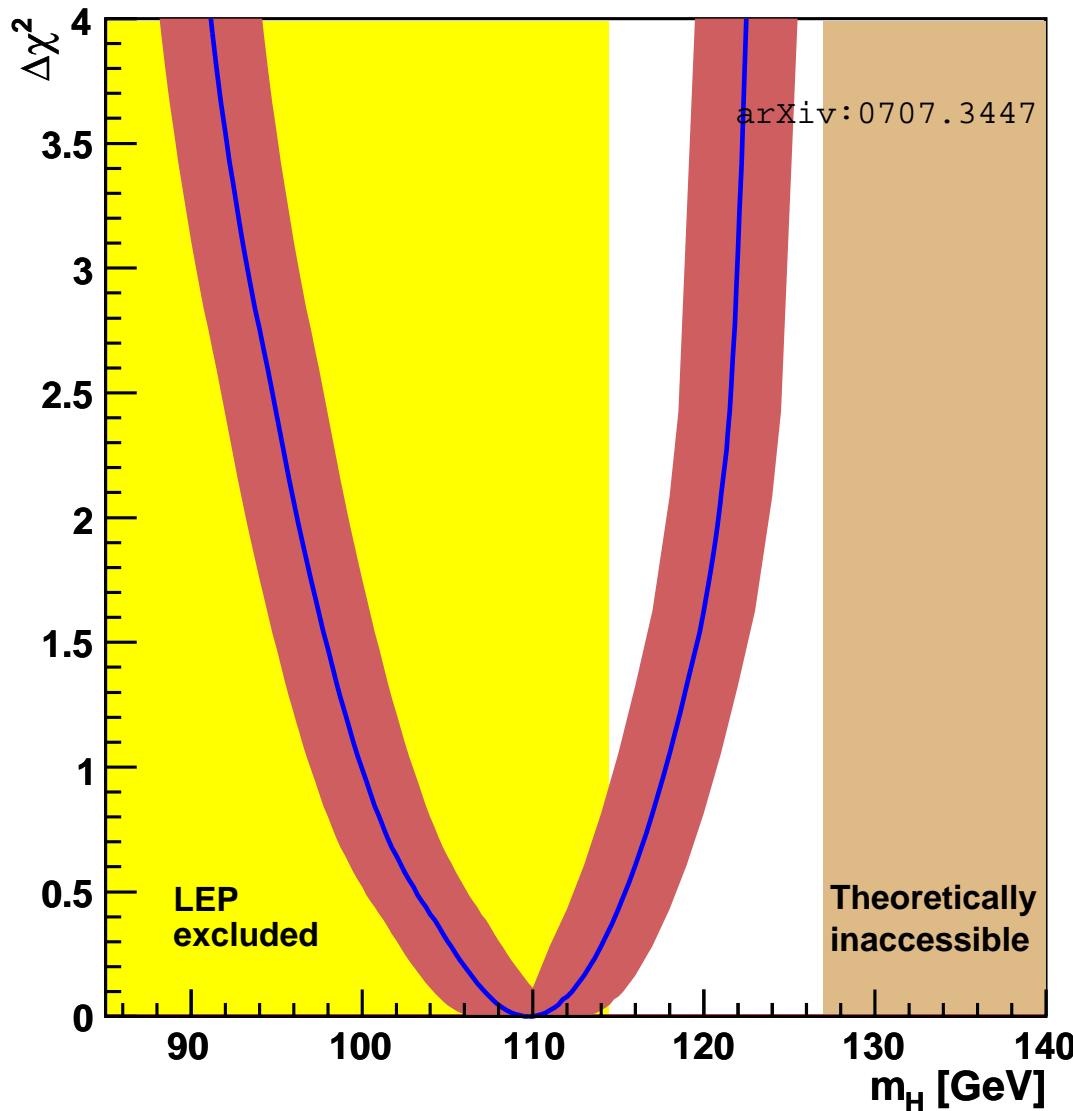


Probabilities: 24% / 20%

15% / 15% (incl. / excl. M_h)

Red band plot:

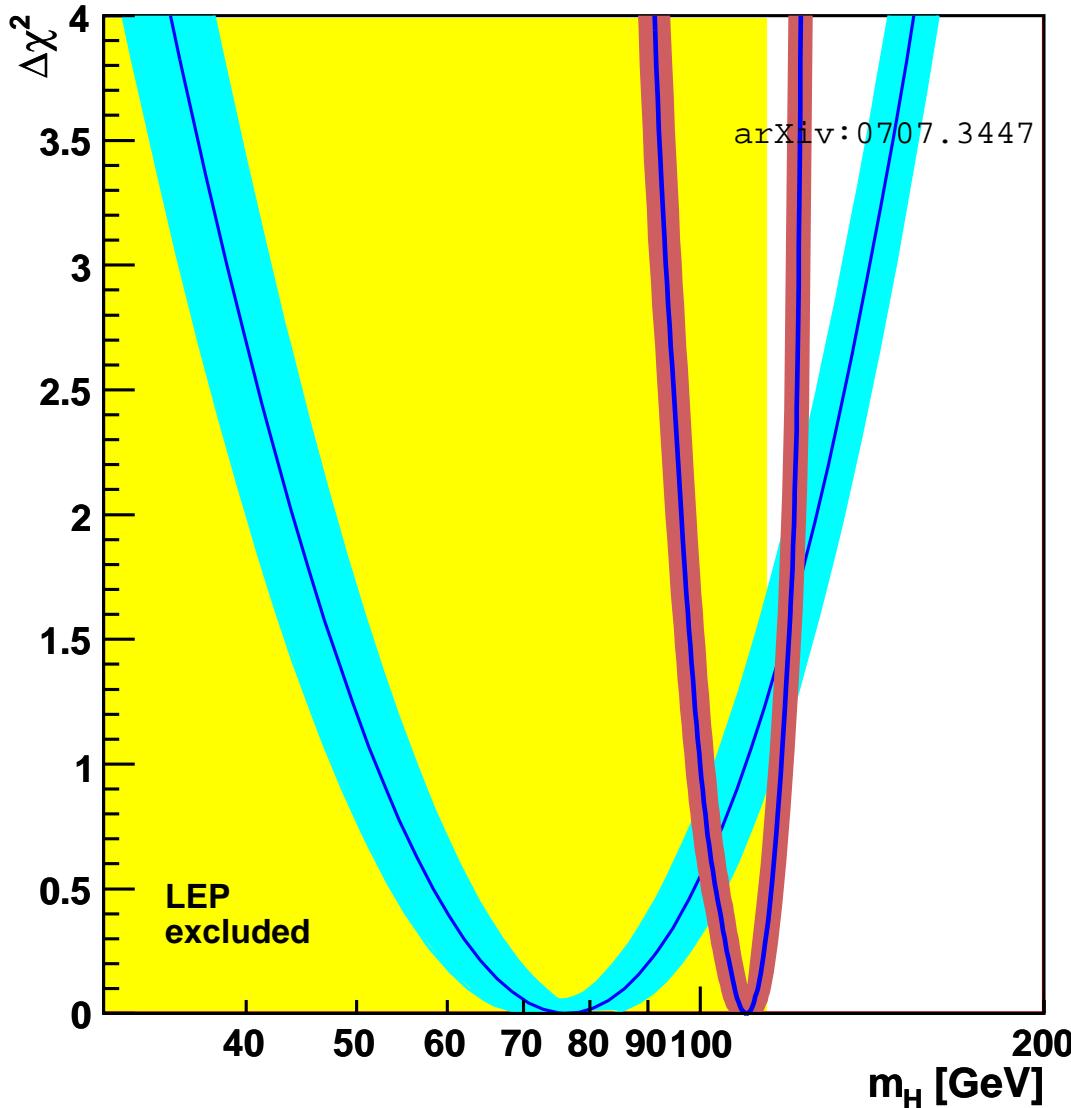
[Buchmüller, Cavanaugh, de Roeck, S.H., Isidori, Paradisi, Ronga, Weber, G. Weiglein '07]



$$M_h = 110^{+8}_{-10} \text{ (exp)} \pm 3 \text{ (theo)} \text{ GeV}$$

Blue/Red band plot:

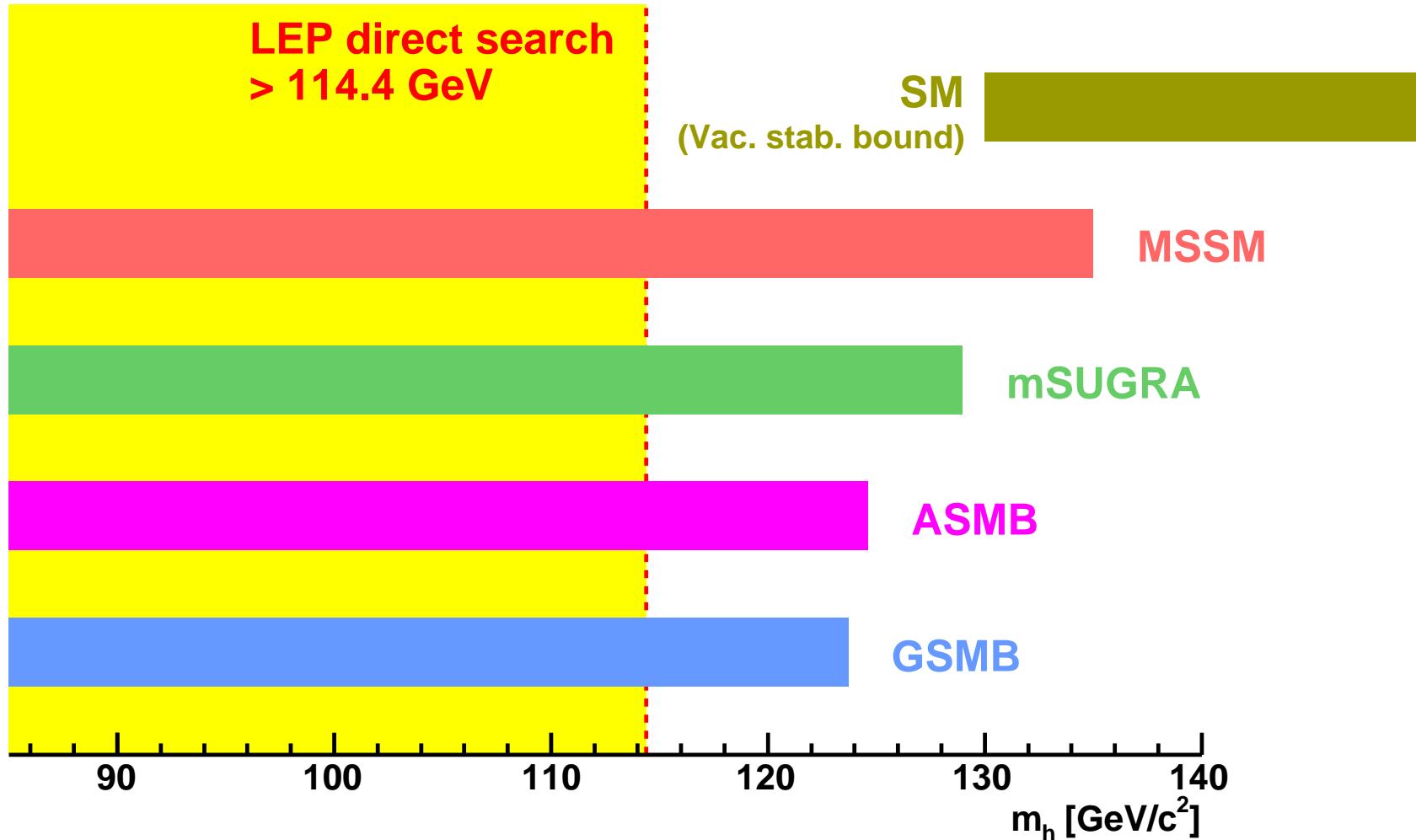
[Buchmüller, Cavanaugh, de Roeck, S.H., Isidori, Paradisi, Ronga, Weber, G. Weiglein '07]



CMSSM (despite its simplicity) is better than the SM

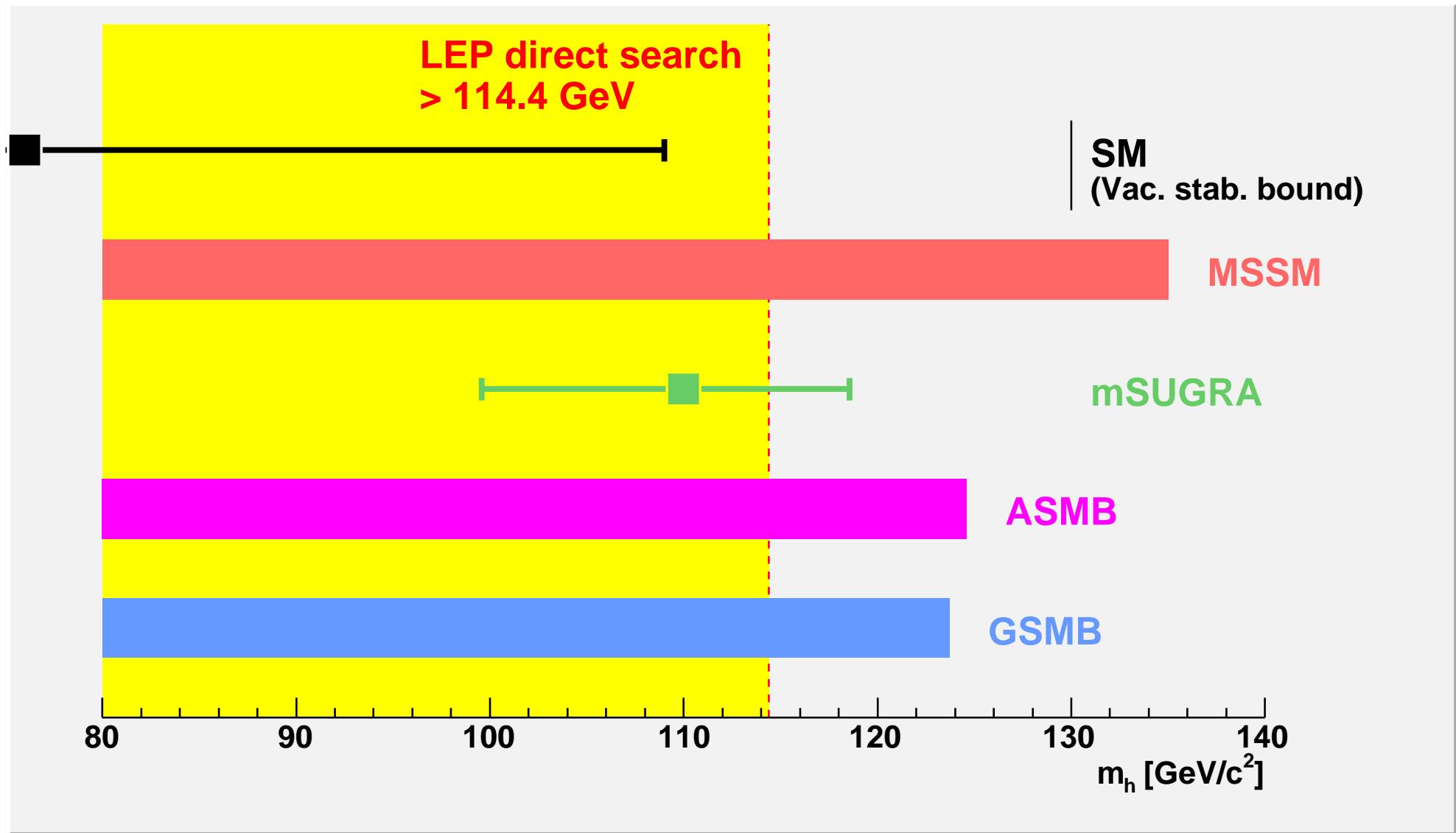
Comparison of allowed ranges for M_h :

[Buchmüller, Cavanaugh, de Roeck, S.H., Isidori, Paradisi, Ronga, Weber, G. Weiglein '07]



Comparison of allowed ranges for M_h :

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6. Conclusions

- Electroweak Precision Physics can give valuable information about the true Lagrangian already now
- Anomalous magnetic moment of the muon:
a 3σ deviation has been established \Rightarrow SUSY?
- Electric dipole moments:
strong restrictions to new complex phases!
- Electroweak precision observables in the SM:
new data for M_W , m_t , ...
Blue band plot: $\Rightarrow M_H^{\text{SM}} = 76^{+33}_{-24}$ GeV (too light for LEP bounds?)
- Electroweak precision observables in the MSSM:
slightly better agreement than within the SM
preference for not too large SUSY scale
Red band plot: CMSSM/mSUGRA: $M_h^{\text{CMSSM}} = 110 \pm 8 \pm 3$ GeV